

Annual Cloud Seeding Report

Western Uintas Program

2020-2021 Winter Season

Prepared For:

Weber Basin Water Conservancy District

Central Utah Water Conservancy District

Provo River Water Users Association

State of Utah, Division of Water Resources

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Report No. 21-12

Project No. 20-456

August 2021



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EXECUTIVE SUMMARY

A total of 25 winter seasons of cloud seeding have been conducted in portions of the western Uinta Range in Utah. The Western Uintas program utilizes 12 ground-based, manually-operated (Cloud Nuclei Generator, or CNG) sites, containing a 2% silver iodide solution. The areas targeted for seeding have included the upper portions of both the Weber River and the Provo River drainages in most years.

Precipitation and snowfall were below normal during the 2020-2021 winter season, with snow water equivalent for the Weber-Ogden River basin averaging about 74% of the median value on April 1st. The water year precipitation through April 1st averaged 67% of the normal (mean value) across the basin. The Provo River basin had corresponding April 1st averages of 78% of median snowpack and 71% of mean precipitation.

A total of 1272.75 CNG hours were conducted during 19 storm periods this season, out of a maximum budgeted 2,500 hours. There was one seeding suspension during the 2020-2021 season, on February 16th due to extreme avalanche danger.

Evaluations of the effectiveness of the cloud seeding program were made for both the past winter season and for the 26 seeded winter seasons combined. These evaluations utilize SNOTEL records collected by the Natural Resources Conservation Service (NRCS) at selected sites within and surrounding the seeded target area. Analyses of the effects of seeding on target area precipitation and snow water content have been conducted for this seeding program, utilizing target/control comparison techniques.

Multi-season target vs. control evaluations have been performed to compare seasonal performance of the target area in comparison to the control areas during both seeded and non-seeded years. These studies have evaluated the performance of two variables related to seasonal storm productivity, namely total seasonal precipitation and April 1 snowpack (measured in inches of liquid water equivalence).

Due to the short period of measurement for total precipitation in the target and control areas prior to the onset of seeding activity this evaluation type is not considered to be as statistically significant and has thus been removed from this report (results for this analysis are available upon request). Both linear and multiple-linear regression comparisons have been developed for the snowpack target vs. control analysis. These evaluations have consistently demonstrated a 3% to 6% increases in April 1st snowpack resulting from cloud seeding efforts.

The results of a thus assumed 5% increase in overall seasonal productivity would yield an average of 0.8" of water across the target area or approximately 25,000 additional acre-feet of runoff. Section 5.0 of the report contains further discussion of these mathematical analyses, and estimates of the likely value and cost/benefit ratio of the seeding program.

THE SCIENCE OF CLOUD SEEDING

The Science

The cloud-seeding process aids precipitation formation by enhancing ice crystal production in clouds. When the ice crystals grow sufficiently, they become snowflakes and fall to the ground.

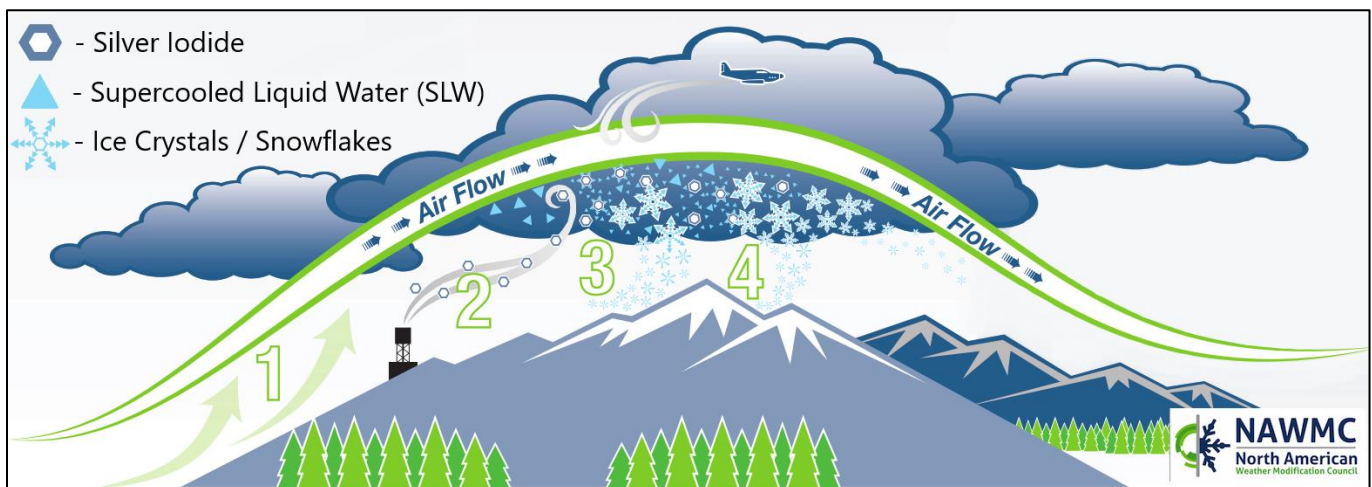
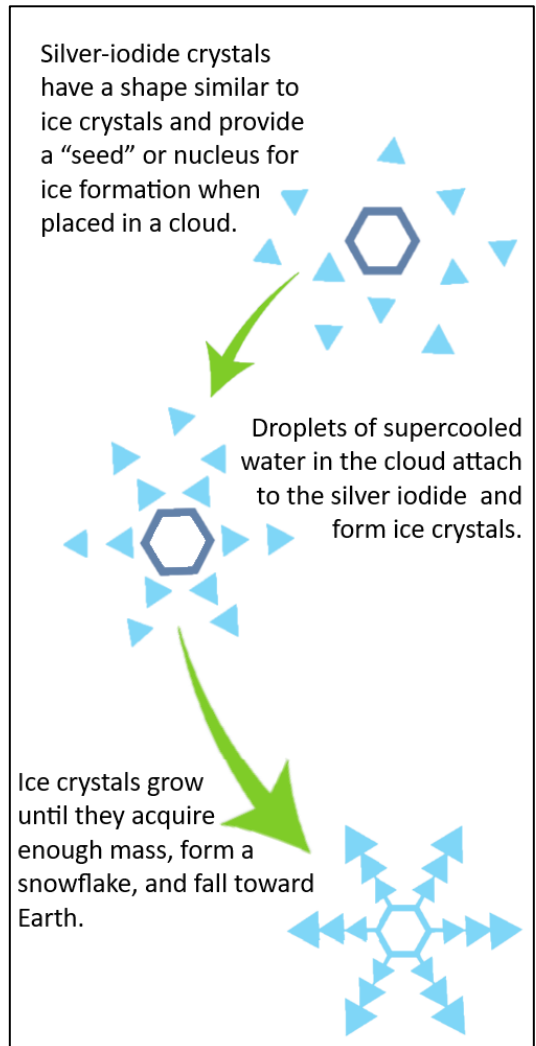
Silver iodide has been selected for its environmental safety and superior efficiency in producing ice in clouds. Silver iodide adds microscopic particles with a structural similarity to natural ice crystals. Ground-based and aircraft-borne technologies can be used to add the particles to the clouds.

Safety

Research has clearly documented that cloud seeding with silver-iodide aerosols shows no environmentally harmful effect. Iodine is a component of many necessary amino acids. Silver is both quite inert and naturally occurring, the amounts released are far less than background silver already present in unseeded areas.

Effectiveness

Numerous studies performed by universities, professional research organizations, private utility companies and weather modification providers have conclusively demonstrated the ability for Silver Iodide to augment precipitation under the proper atmospheric conditions.



STATE OF THE CLIMATE

Every ten years, the National Oceanic and Atmospheric Association (NOAA) releases a summary of various U.S. weather conditions for the past three decades to determine average values for a variety of conditions, including, temperature and precipitation. This is known as the U.S. Climate normal, with a 30-year average, representing the “new normal” for our climate. These 30-year normal values can help to determine a departure from historic norms and identify current weather trends.

The recently released 30-year average ranges from 1990 – 2020. Images in Figure 1 and 2 show how each 30-year average for the past 120 years compares to the composite 20th century average for temperature and precipitation. For the western U.S., the 1990-2020 average shows much warmer than average temperatures, in comparison to the 100-year 20th century average. When comparing precipitation for the past 30 years to both the previous 30-year average and the 1901-2000 average, the American Southwest (including portions of Utah, Arizona, California and Nevada) has seen as much as a 10% decrease in average annual precipitation.

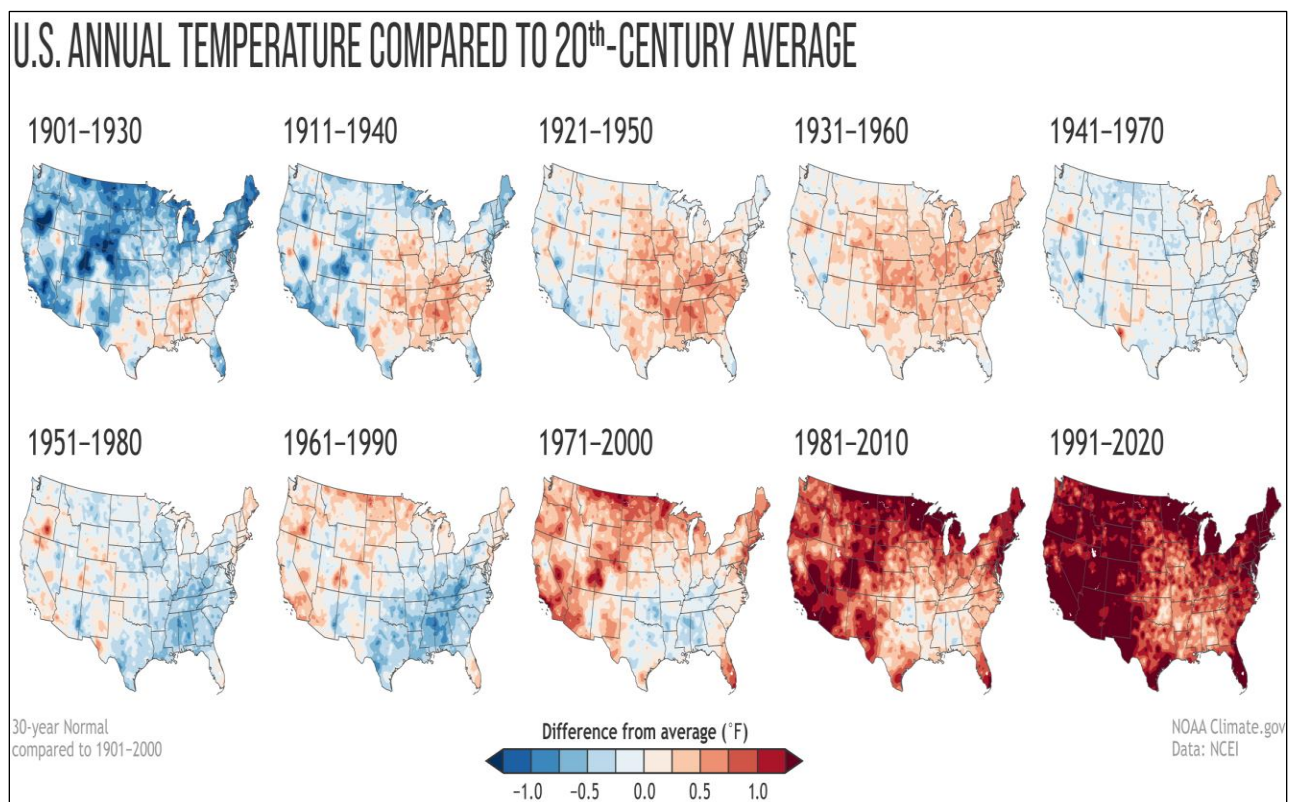


Figure 1 U.S. Annual Temperature compared to 20th-Century Average

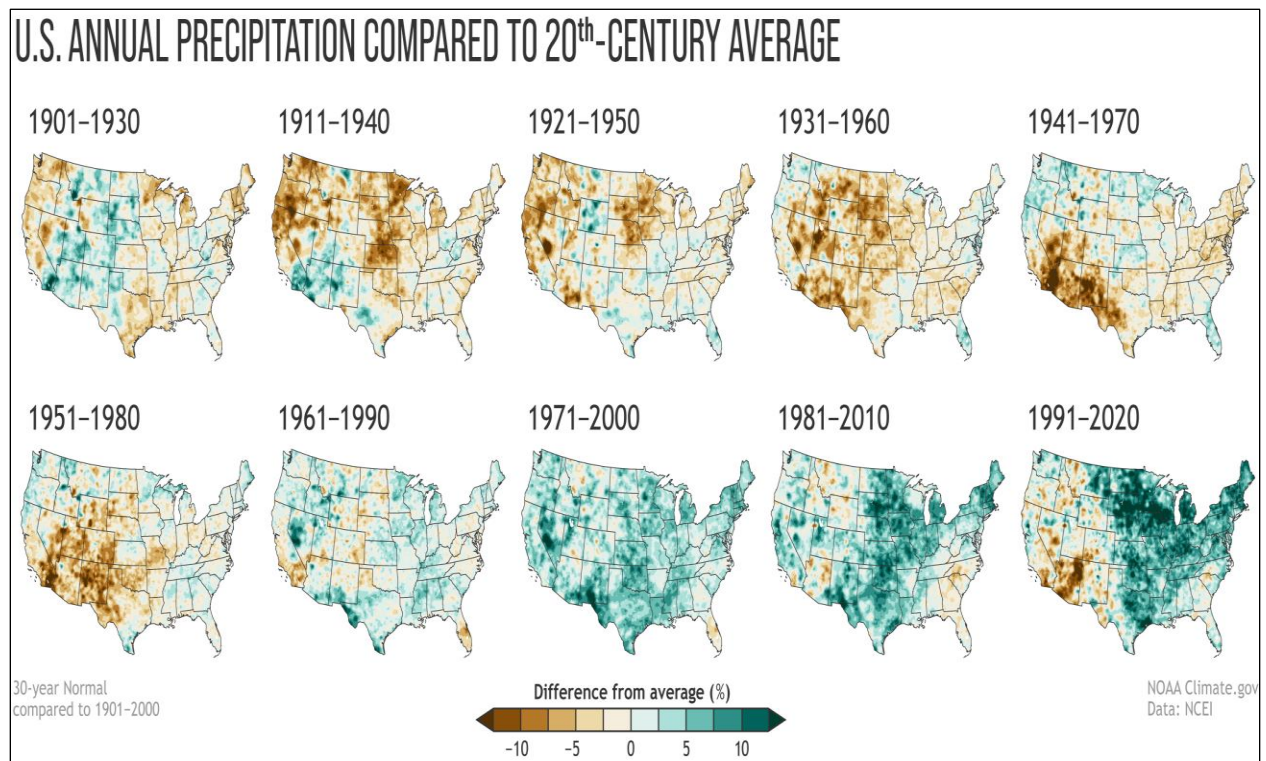


Figure 2 **U.S. Annual Precipitation compared to 20th-Century Average**

1.0 INTRODUCTION

Due to high natural precipitation variability and the increasing demand for water, cloud seeding has been conducted in some parts of Utah for over 40 years, helping to augment water supplies. Cloud seeding in Utah is regulated by the Utah Department of Natural Resources through the Division of Water Resources. After complying with various permit requirements, NAWC was granted a license and permit to conduct cloud seeding for the Western Uintas program watersheds. A cloud seeding program was conducted again during the 2020-2021 winter season for the Upper Weber and Provo River Basins. Cloud seeding programs have been conducted in this area by North American Weather Consultants dating back to 1989. These programs have often been jointly sponsored by two agencies: the Provo River Water Users Association and the Weber Basin Water Conservancy District.

The Weber Basin Water Conservancy District's participation has been continuous since the project's inception while the Provo River Water Users Association opted out during water years 2006 to 2012. The Provo River Water Users Association rejoined the program for the 2012-13 season through the present. Twelve ground-based silver iodide cloud nuclei generators (CNGs) were installed for the 2020-2021 season's program. The main program became operational on December 1, 2020 and ended on March 31, 2021. After discussion with clients, an extension period through much of April was granted, due in part to the ongoing drought in the western United States.

This report provides information about the operational cloud seeding and results of statistical analyses toward estimations of cloud seeding effects. Section 2 describes the seeding project design and provides maps of the seeded target areas, as well as the locations of the CNGs with which the seeding was conducted. Section 3 discusses the types of real-time and forecast meteorological data that are used for conduct of the seeding programs. Section 4 summarizes the seeding operations conducted during this past season. Section 5 details statistical evaluations of the effects of the cloud seeding program.

2.0 PROGRAM DESIGN

2.1 Background

The operational procedures utilized for this cloud seeding project are essentially the same as those that have been proven to be effective for over 40 years of wintertime cloud seeding in the mountainous regions of Utah (Griffith et al., 2009). The results from these operational seeding efforts have consistently indicated long-term average increases in wintertime precipitation and snow water content during the periods in which cloud seeding was conducted. These estimated increases have generally ranged from 5 to 10 percent more than what would have been expected in the absence of seeding, as predicted by historical linear regression target/control analyses.

2.2 Seeding Criteria

Project operations have utilized a selective seeding approach, which has proven to be the most efficient and cost-effective method, and has provided the most beneficial results. Selective seeding, or seeding only of storms or portions of storms in which precipitation has a reasonable chance of being enhanced, is based on several criteria which determine the seedability of the winter storms. These criteria deal with key characteristics of the air mass (temperature, thermodynamic stability, wind flow and moisture content), both in and below the precipitating clouds. The following list provides a summary of NAWC's general seeding criteria.

- Cloud bases are below the mountain barrier crest.
- Low-level wind directions and speeds would favor the movement of the silver iodide particles from their release points into the intended target area.
- No low-level atmospheric inversions or stable layers that would restrict the upward vertical transport of the silver iodide particles from the surface to at least the -5°C (23°F) level or colder.
- Temperature at mountain barrier crest height expected to be -5°C (23°F) or colder.
- Temperature at the 700mb level (approximately 10,000 feet) expected to be warmer than -15°C (5°F).

2.3 Equipment and Project Set Up

In the fall of 2020 NAWC reinstalled ground-based cloud seeding generators for the winter seeding program. The generators were placed at carefully selected sites, to provide seeding plumes that would be effective in enhancing snowfall over the project target area. Climatological winter storm behavior and prevailing wind direction are major factors in the placement of these sites. Twelve seeding sites were installed for this year's seeding program, whose locations are shown in Figure 2.1. Occasionally, seeding sites installed for other seeding programs in the region (such as Northern Utah and High Uintas programs) are used to target the Western Uintas program during less commonly occurring wind flow situations.

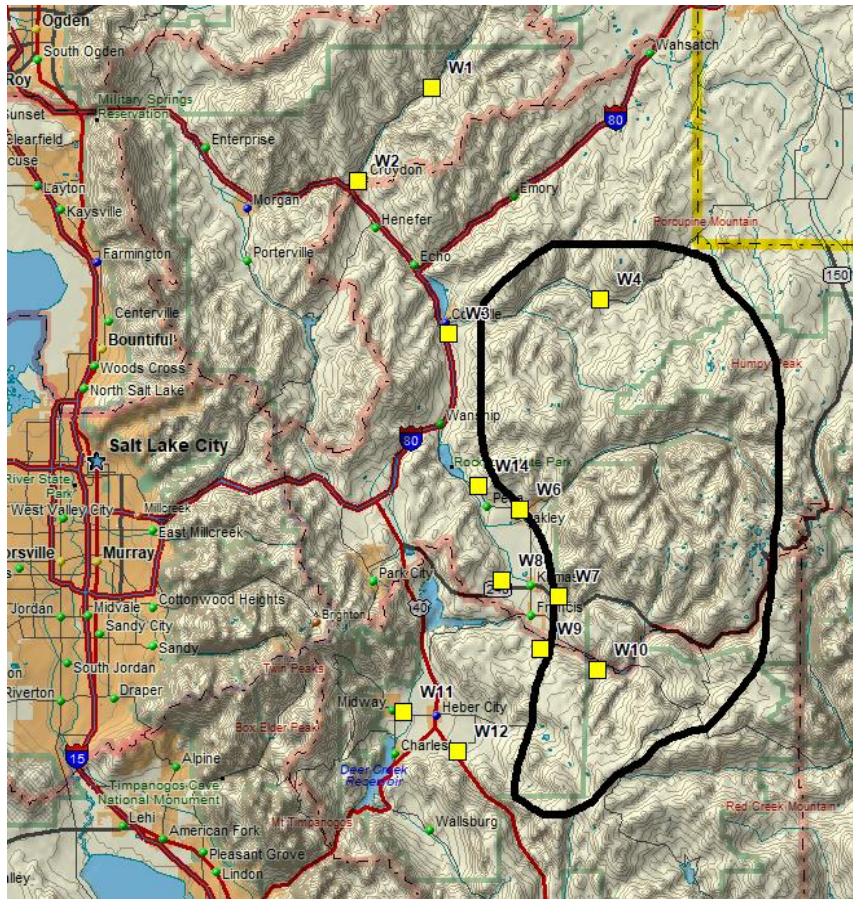


Figure 2.1 Western Uintas target area and ground-based cloud seeding generator locations.

2.3.1 Ground-Based Manual Generators

The cloud seeding equipment consists of a cloud nuclei generator (CNG) unit and a propane gas supply (Figure 2.2). The seeding solution, emitted via combustion, consists of two percent by weight silver iodide (AgI), complexed with small portions of sodium iodide and para-dichlorobenzene in solution with acetone.

The seeding unit is manually operated by igniting the propane flame (at the flame head in a burn chamber) and adjusting the flow of seeding solution through a flow rate meter. The propane gas also pressurizes the solution tank, which allows the solution to be sprayed into the CNG's burn chamber at a regulated rate, where microscopic (sub-micron)-sized silver iodide crystals are formed. The crystals, which closely resemble natural ice crystals in structure, are released at a rate of 8 grams per hour per generator when using the 2% solution. These crystals become active as artificial ice nuclei in-cloud at temperatures between -5°C (23°F) and -10°C (14°F) .

It is necessary that the AgI crystals become active in the formation zone (the region in the cloud which contains supercooled liquid water) upwind of, or over the project area mountain crest. This allows the available supercooled liquid water to be effectively converted to ice crystals which grow to snowflake size and precipitate onto the mountain barrier within the intended area of effect. If the AgI crystals take

too long to become active, or if the temperature upwind of the crest is too warm, the seeding plume will pass from the generator through the precipitation formation zone and over the mountain crest without producing any additional snowfall at the surface. It is the meteorologist's task to identify storm situations in which the seeding treatment can be effective.



Figure 2.2 Manually operated cloud seeding generator

Cloud seeding generators were sited at 12 locations (mostly in the valleys), ranging from the southwest to northwest sides of the target area, as shown in Figure 2.1. Pertinent CNG site information is provided in Table 2-2. Most of the winter storms that affect the northern Utah Mountains are associated with synoptic weather systems that move into Utah from the northwest, west or southwest. Usually they consist of a frontal system and/or an upper trough with the winds preceding the front or trough blowing from the south or southwest. As each system passes through the area, the wind flow changes to the west, northwest, or north. Clouds and precipitation may precede as well as follow the front/trough passage, or they may occur primarily after the passage along the boundary of the colder air mass that moves into the region. For the region comprising the project target area, the most abundant precipitation and low-mid

level moisture usually occurs in west to northwest flow patterns. This is when the best seeding opportunities typically occur. Southwesterly flow is generally associated with somewhat warmer conditions that are sometimes less seedable.

**Table 2-2
Cloud Seeding Generator Sites**

Site ID	Site Name	Elev (Ft)	Lat (N)	Long (W)
1	Lost Creek Reservoir	5525	41° 07.10'	111° 29.32'
2	Croyden	5371	41° 04.12'	111° 30.83'
3	Coalville	5587	40° 55.95'	111° 20.72'
4	Pineview	6407	40° 56.39'	111° 10.18'
6	Oakley	6472	40° 43.07'	111° 18.00'
7	Kamas	6489	40° 38.43'	111° 16.77'
8	Kamas West	6872	40° 38.16'	111° 19.33'
9	Woodland	6706	40° 34.89'	111° 13.81'
10	Woodland East	7305	40° 33.35'	111° 06.80'
11	Midway	5570	40° 30.59'	111° 28.64'
12	Heber City	5810	40° 29.73'	111° 22.52'
14	Peoa	6148	40° 43.75'	111° 20.61'

2.3.2 Suspension Criteria

NAWC always conducts its projects within guidelines adopted to ensure public safety. Accordingly, NAWC has a standing policy and project-specific procedures for the suspension of cloud seeding operations in certain situations. Those criteria are shown in Appendix A, and have recently been updated in coordination with the Utah Division of Water Resources. The criteria are an integral part of the seeding program. There was one instance during the 2020-2021 season where suspension criteria were met: on February 16, during a storm event, seeding operations were prematurely ended when an Extreme Danger Avalanche Warning was issued for most of the mountain ranges in Utah, including the Uintas.

3.0 WEATHER DATA AND MODELS

NAWC maintains a fully equipped project operations center at its Sandy, Utah headquarters. Meteorological information is acquired online from a wide variety of freely available sources and subscriber services. This information includes weather forecast model data, surface observations, rawinsonde (weather balloon) upper-air observations, satellite images, NEXRAD radar information, and weather cameras. This information helps NAWC's meteorologists to determine when conditions are appropriate for cloud seeding. NAWC's meteorologists are able to access all meteorological products from their homes, allowing continued monitoring and conduct of seeding operations outside of regular business hours.

Figures 3.1 – 3.3 show examples of some of the available weather information that was used in this decision-making process. Figure 3.4 displays predictions of ground-based seeding plume dispersion for a discrete storm period in the Western Uintas Program from the 2019-2020 season using the National Oceanic and Atmospheric Administration's HYSPLIT model. This model helps to estimate the horizontal and vertical spread of a plume from potential ground-based seeding sites based on wind fields contained in the weather forecast models.

Global and regional forecast models are a cornerstone of modern weather forecasting, and important tools for operational meteorologists. These models forecast a variety of parameters at different levels of the atmosphere, including winds, temperatures, moisture, and surface parameters such as accumulated precipitation. An example of a display from the global GFS forecast model for a storm event during the 2019-2020 season is shown in Figure 3.5.

A more recent meteorological product utilized by NAWC to improve operational efficiency is a customized High-Resolution Rapid Refresh (HRRR) model data display and analysis package, developed by Idaho Power Company. The HRRR contains important atmospheric parameters in much finer time and space resolution than other (e.g. global) weather forecast models. Most importantly, this model identifies the presence of supercooled liquid water, the primary target of cloud seeding. NAWC is working closely with the Atmospheric Research Center at Utah State University to aid in the development of a forecast model that will predict or forecast relative concentrations of supercooled liquid water in storms developing over the Uinta Range.

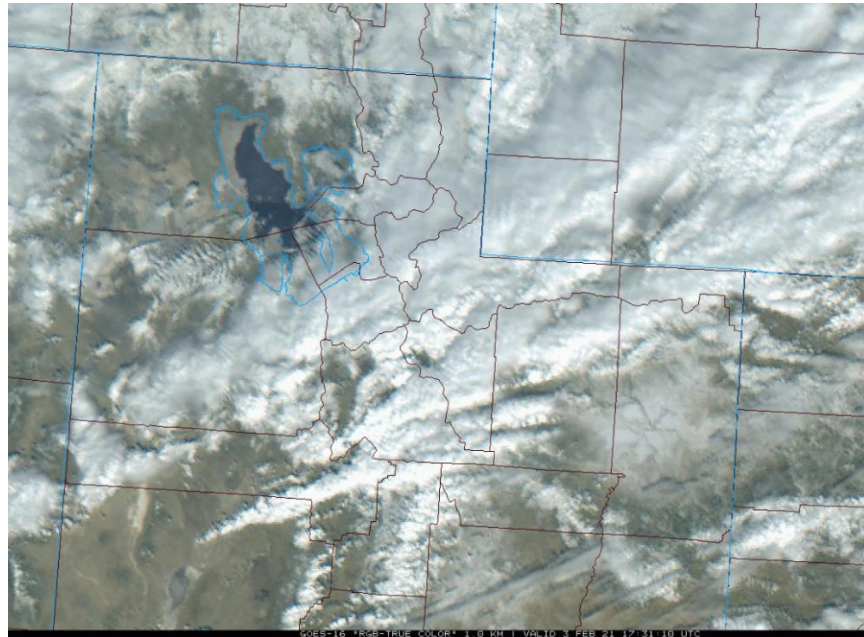


Figure 3.1 Visible spectrum satellite image of northern Utah on February 3, 2021 during a seeded event.

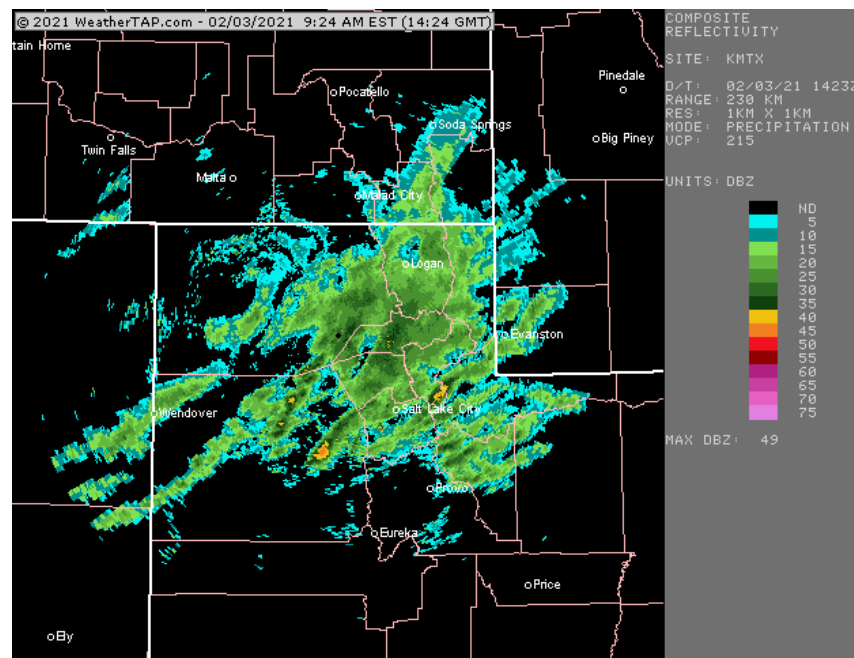


Figure 3.2 Weather radar image over northern Utah, on the morning of February 3, 2021. Image courtesy of Weathertap.com .

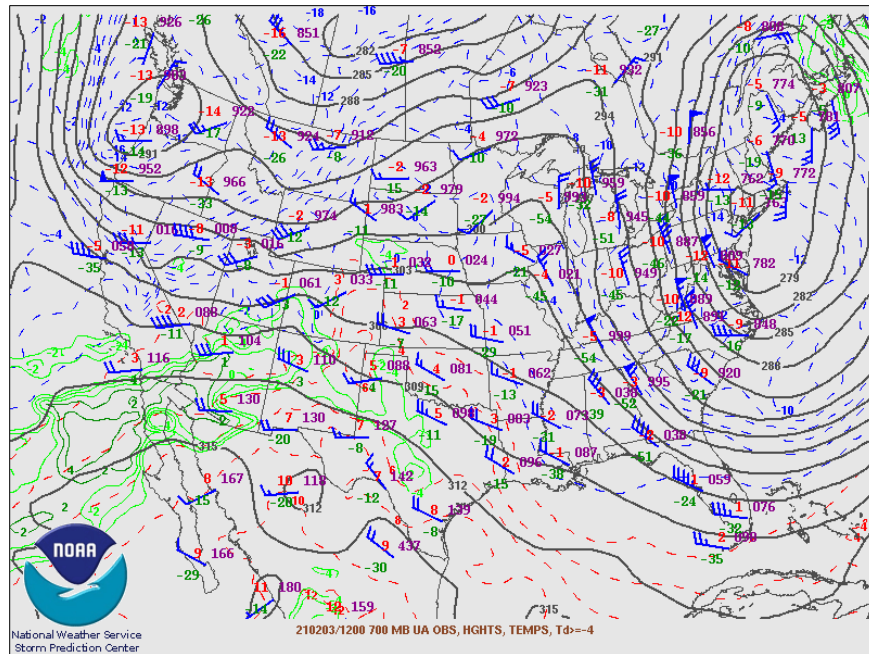


Figure 3.3 U.S. 700 mb map on February 3, 2021, illustrating the larger scale weather pattern across the region. This map includes variables such as 700 mb height, winds, temperature and moisture fields. Courtesy of NOAA Storm Prediction Center website, <http://www.spc.noaa.gov> .

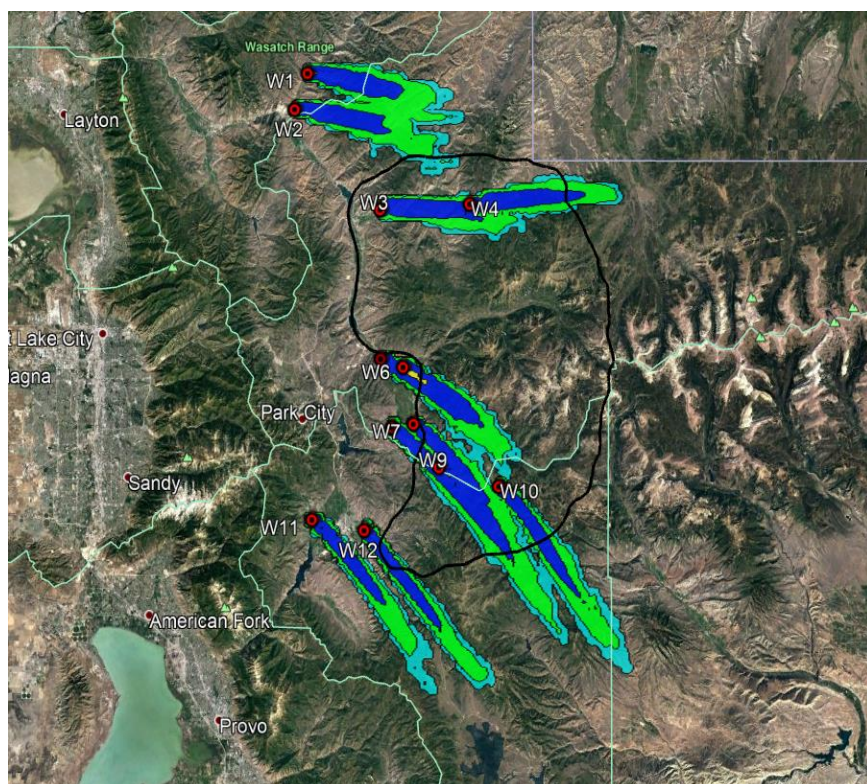
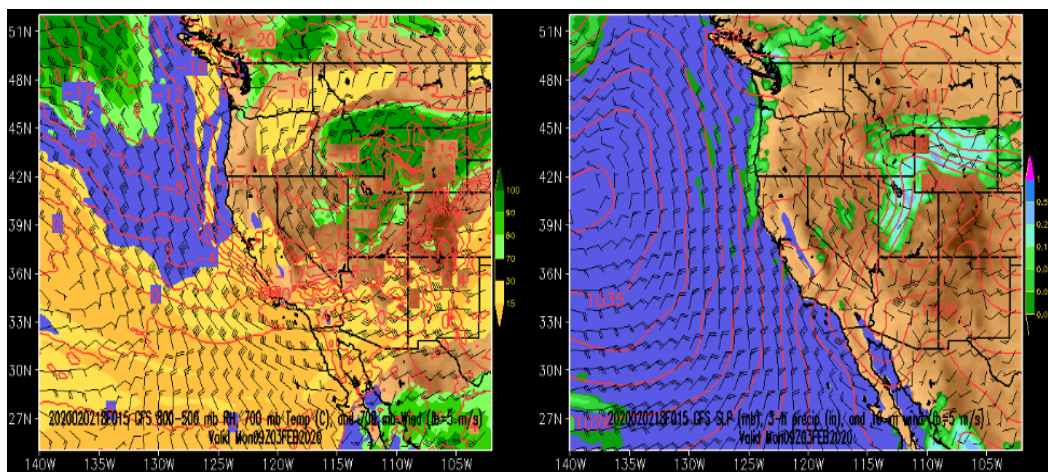


Figure 3.4 HYSPLIT plume dispersion forecast from individual ground generator sites during a storm period early on February 3, 2020 from all potential sites. These plots can help the meteorologist to select the appropriate sites to utilize in a given situation.



Figures 3.5 GFS (Global Forecast Systems) model plot during a storm event on the night of February 2-3, 2020. These types of plots provide analyses and forecasts for things such as wind, temperatures, moisture at various levels of the atmosphere, as well as surface parameters such as accumulated precipitation.

4.0 OPERATIONS

The 2020-2021 Western Uintas cloud seeding program for the Weber and Provo River basins began on December 1, 2020 and ended on March 31st, 2021; after discussions with the clients regarding the western U.S. drought, an extension of the program into April was granted. A total of 19 storm periods were seeded during all or portions of 31 days: three storms were seeded in December, three in January, five in February, five in March and three during the April extension period. A total of 1272.75 seeding generator hours were conducted this season. There was one brief suspension during the season, on February 16 due to extreme danger avalanche conditions. Table 4-1 shows the dates and ground generator usage for the storm events, and Appendix B contains more detailed site usage data. Figure 4.1 shows the usage of generator hours during the season.

Precipitation and snowfall were below normal during the 2020-2021 winter season, with snow water equivalent for the Weber-Ogden River basin averaging about 74% of the median value on April 1. The water year precipitation through April 1 averaged 67% of the normal (mean value) across the basin. The Provo River basin had corresponding April 1 averages of 78% of median snowpack and 71% of mean precipitation. Figures 4.2 to 4.4 are seasonal graphs for some SNOTEL sites in the target area.

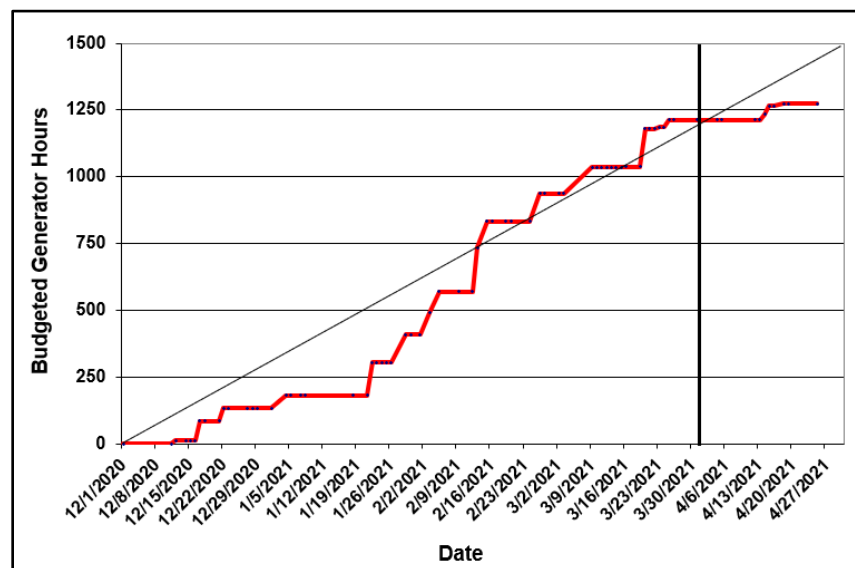


Figure 4.1 Seeding during the 2020-2021 season (red), in comparison to a linear usage of budgeted hours through the season (diagonal line). Vertical black line denotes beginning of extension period.

Table 4-1
Storm dates and number of generators used,
2020-2021 season.

Storm No.	Date(s)	No. of Generators Used	No. of Hours
1	December 12	3	11.50
2	December 17-18	6	72.25
3	December 22-23	3	49.50
4	January 4-5	4	48.00
5	January 22-23	6	122.75
6	January 29-30	8	104.00
7	February 3	9	81.50
8	February 5	8	80.25
9	February 13-14	9	164.25
10	February 15-16	5	98.00
11	February 26-27	8	105.00
12	March 9-10	7	97.75
13	March 16	1	3.00
14	March 20-21	8	140.75
15	March 23	1	6.75
16	March 25-26	5	28.50
17	April 14	3	20.25
18	April 15-16	6	30.75
19	April 19	2	8.00
Season Total	---	---	1272.75

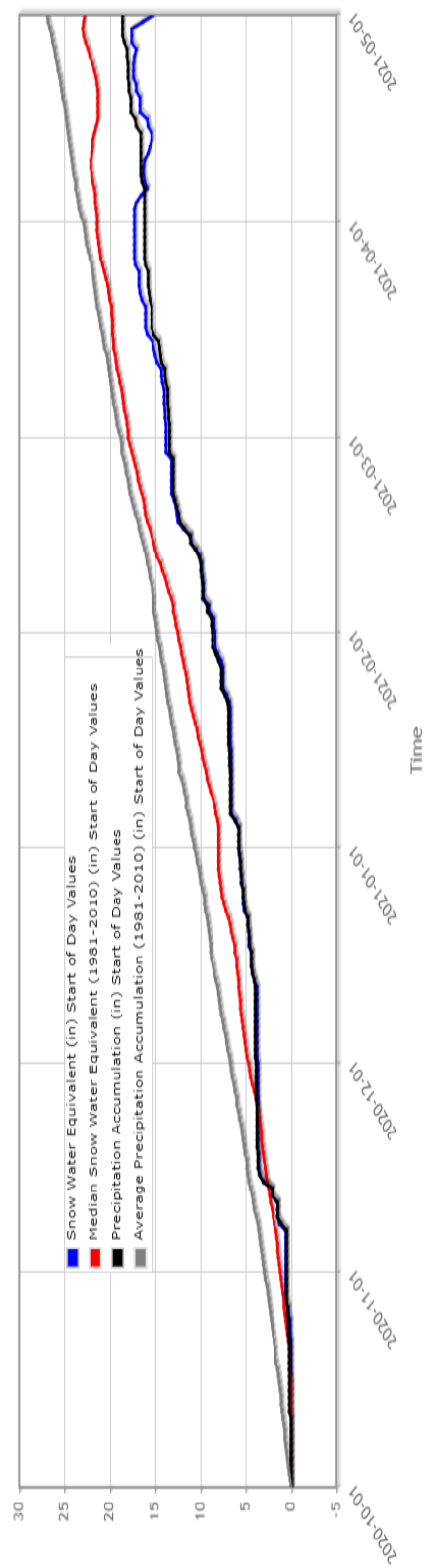


Figure 4.2 NRCS SNOTEL snow and precipitation plot for October 1, 2020 through May 1, 2021 for Trial Lake, UT.

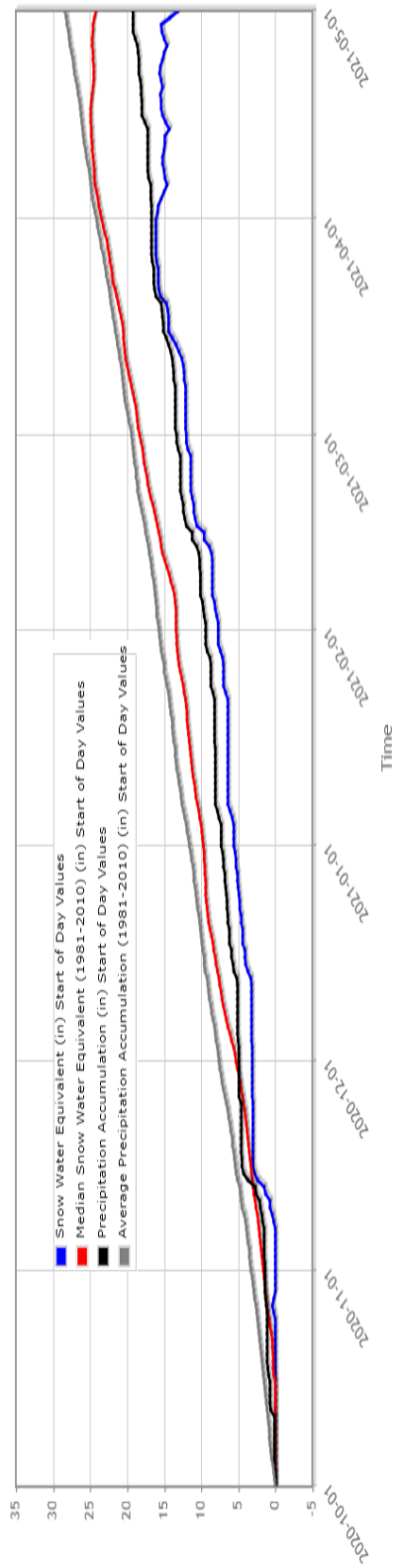


Figure 4.3 NRCS SNOTEL snow and precipitation plot for October 1, 2020 through May 1, 2021 for Chalk Creek #1, UT.

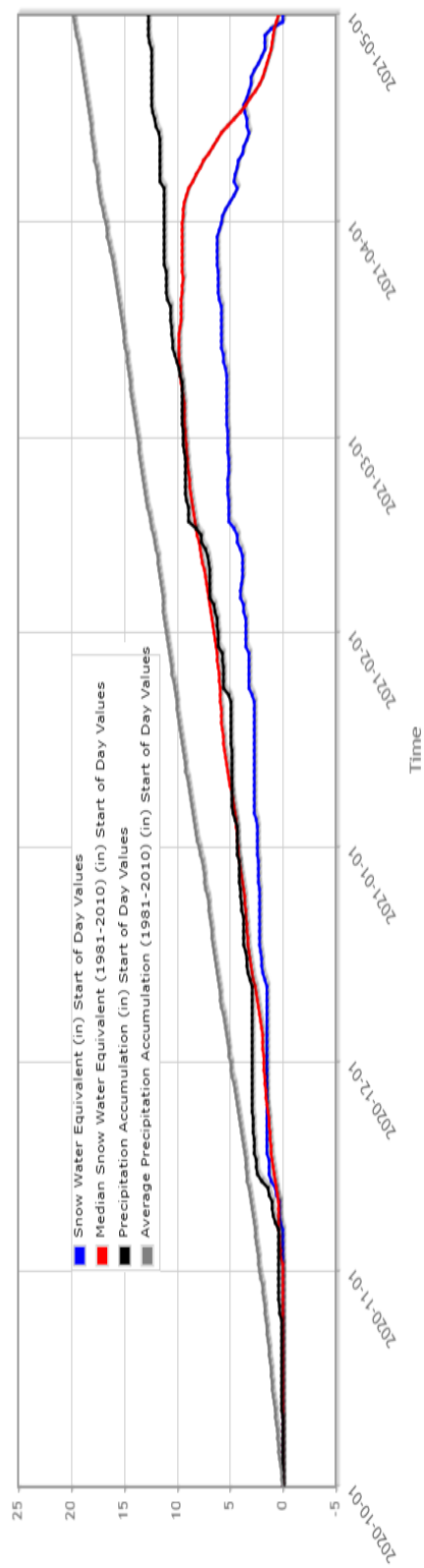


Figure 4.4 NRCS SNOTEL snow and precipitation plot for October 1, 2020 through May 1, 2021 for Beaver Divide, UT. 4.1 Operational Procedures

In operational practice, the project meteorologist, with the aid of continually updated online weather information, monitored each approaching storm. If the storm parameters met the seedability criteria presented in Table 2-1, and if no seeding curtailments or suspensions were in effect, an appropriate array of seeding generators was ignited and then adjusted as evolving conditions required. Seeding continued as long as conditions were favorable and precipitating clouds remained over the target area. The operation of the seeding sites is not a simple “all-or-nothing” situation. Individual seeding sites are selected and run based on their location, and targeting considerations based on storm attributes.

4.1 Operational Summary

A brief synopsis of seeded (or otherwise significant) storm events during the operational seeding period is provided below. All times are local (MST/MDT) unless otherwise noted. References to wind direction in meteorology correspond to the direction that the wind is coming from (the upwind direction). The 700 mb level (~9,500 feet above sea level during the winter) temperature in the atmosphere is often referenced, given that the temperature near mountain crest height is an important consideration for cloud seeding.

December 2020

December brought below normal precipitation/snowfall, despite a typical volume of storm systems for December affecting Utah. There were three seeded storm events during the month. Figure 4.5 shows December 2020 precipitation across the region as a percentage of average (mean) monthly totals.

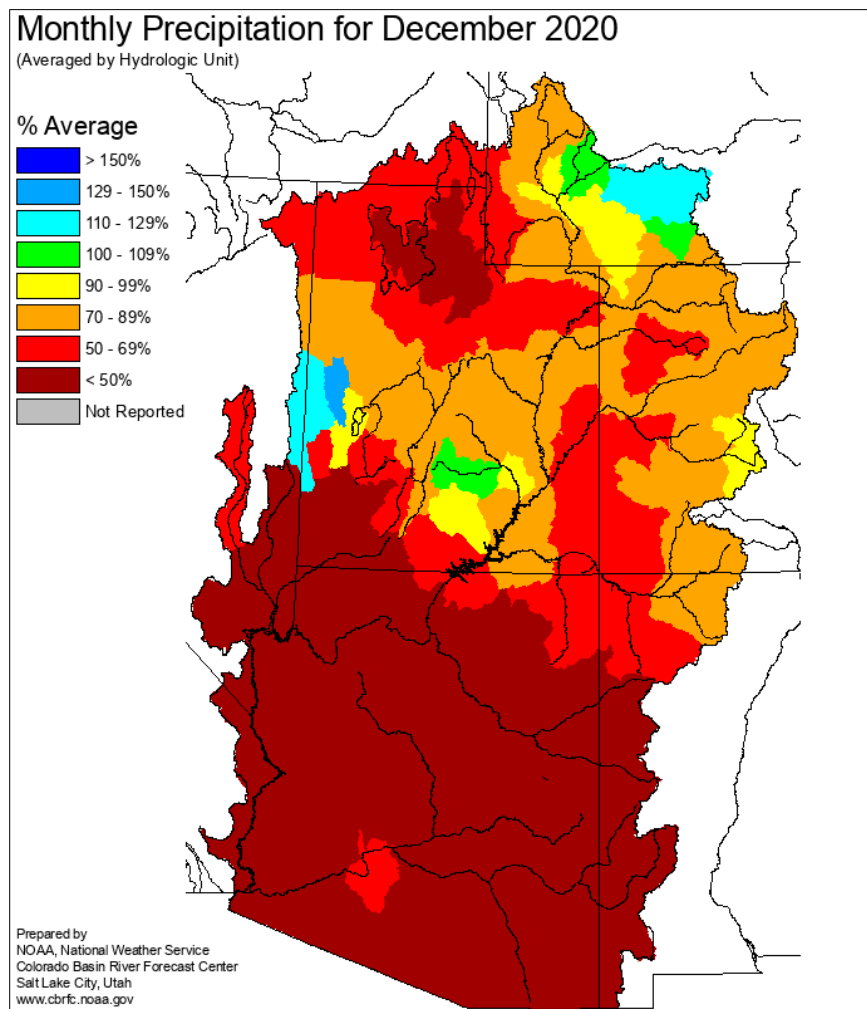


Figure 4.5 December 2020 precipitation, percent of normal

A shortwave disturbance riding southeast through a longwave trough covering the western two-thirds of the country began to push into the Great Basin on the 11th, with moisture ahead of the system spreading into Utah during the evening and overnight hours into the 12th. Light snow spread across the area, but light winds were not favorable for seeding transport into the clouds during the first part of the storm event. As the axis of the disturbance passed through the Uintas in the morning hours of the 12th, north to northwest flow began to set up with bands of snow showers developing and pushing into the target area. A few generator sites were activated for this second part of the storm event, running from late morning into the latter part of the afternoon before activity tapered off.

Another disturbance began to affect the entire state during the morning and early afternoon hours of the 17th, but the airmass below 700 mb was stable and thus, not ideal for seeding operations. Similar to the previous storm, as the axis of the disturbance passed through the area, the wind flow became northwesterly, temperatures aloft cooled and the airmass became unstable, allowing for snow showers to develop and move into the Western Uintas. Several CNG sites were activated during the evening hours and continued to run overnight into the morning hours of the 18th, by which time

precipitation came to an end. Areal observations indicated a tenth to nearly a half inch of liquid water equivalent was recorded.

A fast-moving disturbance accompanied by a strong cold front moved across the state during the afternoon of the 22nd. Initially, temperatures aloft were rather warm for late December, but after the passage of the cold front, temperatures fell sharply and moist, unstable northwest flow developed in its wake. Snow developed, enhanced by a “backside” area of lift that continued to bring snow to the mountains of northern Utah. CNG sites were activated in the afternoon of the 22nd and continued to run until the morning of the 23rd, when precipitation tapered off. Up to 0.6” of liquid water equivalent were recorded in the target area.

January 2021

January weather patterns continued those of December 2020, with below normal precipitation/snowfall amid a lower-than-average number of storm systems affecting the state. Figure 4.6 shows January 2021 precipitation across the state as a percentage of average (mean) monthly totals.

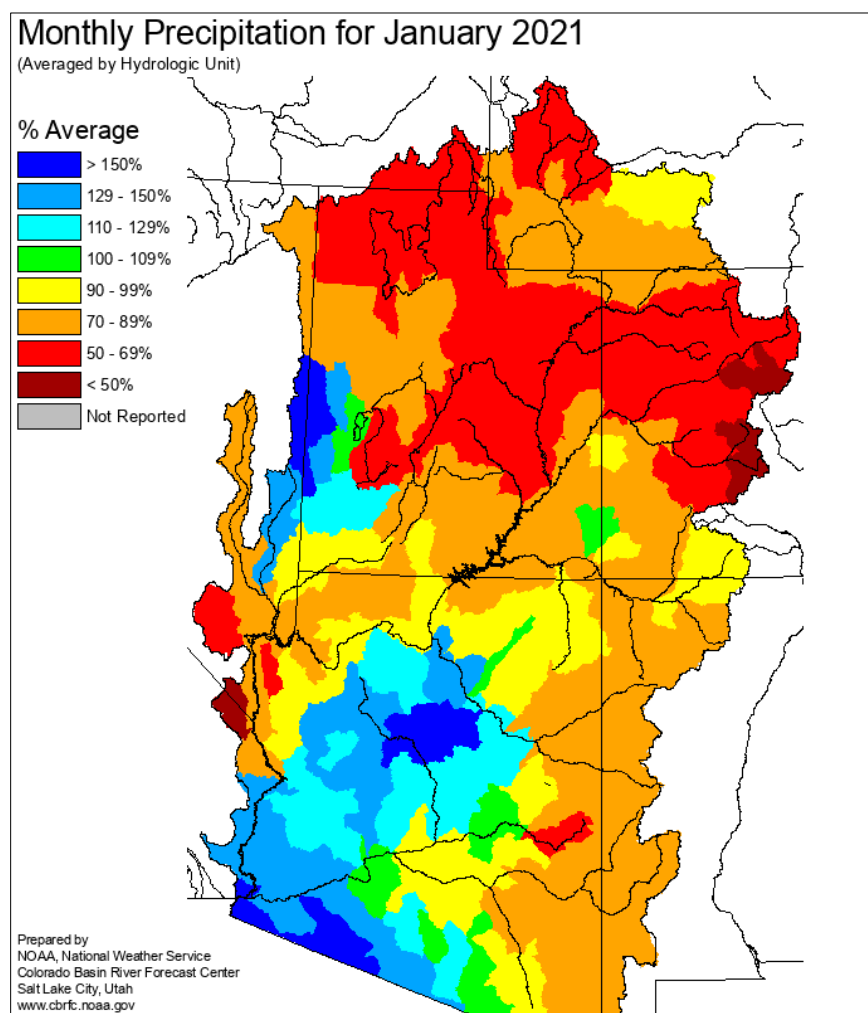


Figure 4.6 January 2021 precipitation, percent of normal

A trough of low pressure pushed inland across the Pacific Northwest late on January 3rd/early 4th and quickly advanced eastward toward Utah. Warm advection on the forward side of the trough was accompanied by an increase in moisture aloft, with radar indicating widespread precipitation by evening across northern Utah; unfortunately, the lower levels of the atmosphere were dry so much of the precipitation was not reaching the ground. As the cold front approached, a band of precipitation developed along it across northern Nevada with lightning noted near Winnemucca, an attestation of the energetic nature of the approaching front. Several sites were activated on the southern end of the target area in anticipation of overnight precipitation ramping up, which did occur as the front began to push across northern Utah. The icing meter at Dry Ridge in the High Uintas did record several icing cycles between 2100 MST and 0230 MST, an indication of the presence of supercooled liquid water. Snow continued overnight into the early morning of the 5th before tapering off. Brief light northwest flow snow showers developed later in the day but were insignificant. Storm total precipitation was generally in the 0.1-0.5" range (liquid water equivalent). After this event, a prolonged period of dry weather affected most of Utah.

The next storm system began to impact Utah early in the afternoon of January 22nd. An upper-level trough was digging into central California with a lead shortwave disturbance near San Francisco. Ahead of the trough, upper-level diffluent flow and moisture advection across Utah was resulting in an expanding area of precipitation. 700 mb temperatures were marginally sufficient for seeding criteria, at -5°C. Precipitation continued into the evening with several CNG sites activated as better wind flow was observed by that time. Precipitation continued overnight and into the morning of the 23rd, with south and southwest-facing slopes seeing the brunt of the snowfall. Snow showers continued into the afternoon hours before tapering off, at which time CNG sites were shut off. Storm total precipitation ranged from 0.5"-1.2" of snow water equivalent.

The third and final storm to impact Utah for January approached on the afternoon of the 29th. Moist and relatively warm southerly flow ahead of the approaching trough of low pressure began to spread precipitation across the state, but warm mid-level temperatures (700 mb temp -2°C) and light, erratic low-level winds precluded seeding operations during this part of the event. By evening, as the trough axis passed across the area, winds veered around to northwesterly, and temperatures cooled off. Moist upslope flow on northwest-facing slopes produced widespread snow showers across the target area. Several sites were activated in the evening and continued to operate until the morning of the 30th, when precipitation tapered off as the trough exited the area. Total snow water equivalent (SWE) for this event ranged from 0.3"-0.7".

February 2021

Precipitation in February was above average across the target area, with five seeding opportunities during an active month, weatherwise. Figure 4.7 shows the percentage of normal February precipitation across the region.

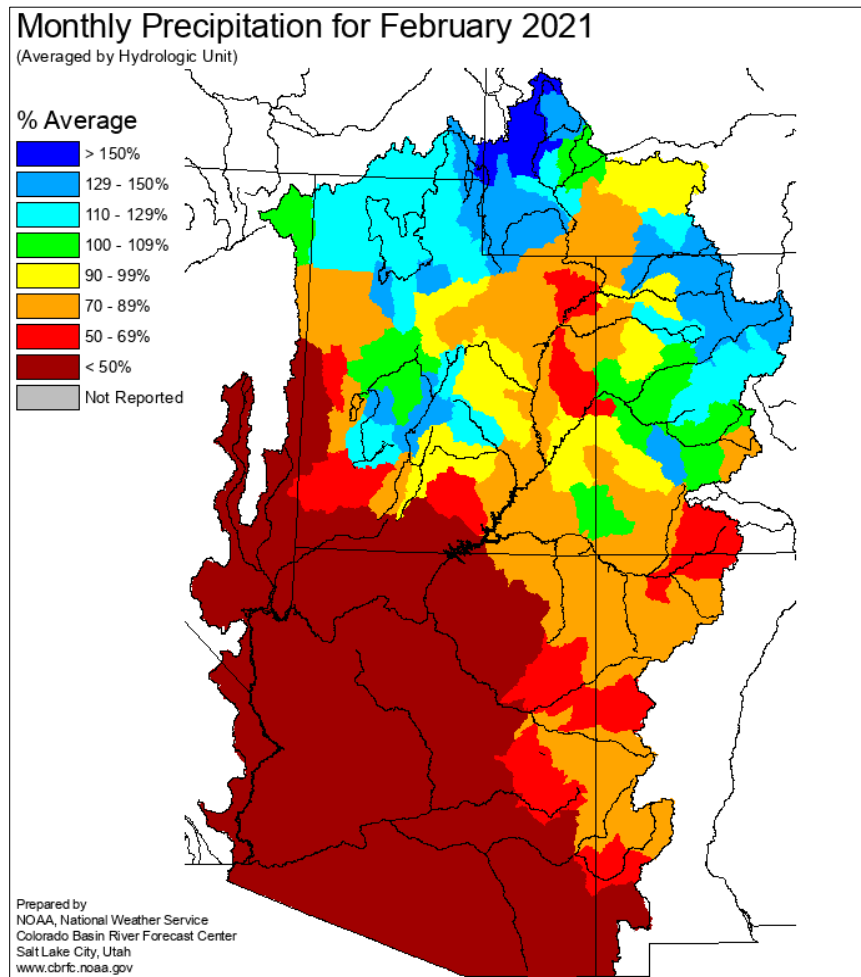


Figure 4.7 February 2021 precipitation, percent of normal

Early on February 3, the northern and more potent piece of a splitting west coast upper-level trough began to approach Utah. Ahead of the trough axis, a strong cold front and associated precipitation pushed into northern Utah during the morning hours with isolated lightning strikes observed. While it was relatively warm ahead of the frontal boundary – 700 mb temperatures were around -3°C – temperatures dropped fairly quickly behind the front with west to northwest flow becoming established, providing for great orographic lift over the mountains. Several sites were activated towards the latter part of the morning and continued to operate through the afternoon, shutting off during the evening as precipitation tapered off. SWE totals from this event were in the 0.25”-0.75” range.

A shortwave disturbance approached northern Utah early in the morning of February 5th, with light snow in advance of the system spreading across the area. 700 mb temperatures were ideal, around -10°C . Although surface winds were fairly light and variable, winds just above the surface were stronger and more favorable for proper targeting with the seeding plumes. CNG sites were activated around mid-morning and continued through the afternoon as snow continued across much of the area. As the

disturbance pushed further away from the area during the evening, the upslope flow weakened and snow diminished, at which time sites were shut off. Total SWE from this storm event ranged from 0.25" to 1.00" in some spots.

Diffluent flow and warm/moist southwesterly flow ahead of an upper-level trough over central California began to produce areas of precipitation across Utah early in the morning of February 13th. The morning sounding from SLC indicated marginally sufficient 700 mb temperatures (-6°C) with no stability issues present. Several CNG sites were activated in the morning, with a couple more in the afternoon and early evening as snow continued across the area. The trough axis pushed through around mid-afternoon with winds becoming northwesterly and, eventually northerly by evening. Snow continued overnight, ending early in the morning on the 14th. Storm total SWE ranged from 0.10" to as much as 1.00".

Quick on the heels of the previous disturbance, the next storm system to affect Utah began to approach from the northwest during the day on February 15th. Strong northwesterly winds aloft were in place over Utah, with warm/moist advection occurring at lower levels promoting an area of precipitation that spread across northern Utah during the day. As the axis of the shortwave disturbance passed across the area late in the afternoon, winds became northwesterly and moist upslope flow commenced with snow intensifying for west/northwest facing slopes. Several CNG sites were activated in the evening and continued to run overnight with ideal atmospheric parameters in place for seeding. On the 16th, snow began to decrease in coverage during the morning, but picked up again substantially in the early afternoon as a second shortwave disturbance approached. Unfortunately, seeding operations had to come to an abrupt end in the middle of the storm event as the assessed danger of avalanches had reached the Extreme category. Snowfall continued through the evening of the 16th and into the morning of the 17th before finally tapering off. Storm total SWE ranged from 0.40" to 1.60".

The last storm event of the month took place beginning on February 26th. An upper-level trough over the interior Pacific Northwest moved into the Great Basin during the afternoon/evening hours. A strengthening cold front ahead of the trough moved into northern Utah late in the afternoon accompanied by a band of snow showers. West to northwest flow behind the front was ideal for upslope flow to generate additional snow, and several CNG sites were activated early in the evening. Snow continued overnight into the morning hours of the 17th, with sites shut down around 0800 MST as the morning sounding from SLC indicated that 700 mb temperatures had fallen to -16°C, indicative that any clouds present were likely to already have sufficient ice crystals in them and little in the way of supercooled water. Storm total SWE was between 0.10" and 0.50".

March 2021

March saw below-normal precipitation across most of the area, despite storm systems affecting the area on a regular basis during the month. There were five seeded storm periods in March. Figure 4.8 shows the regional March precipitation as a percentage of normal.

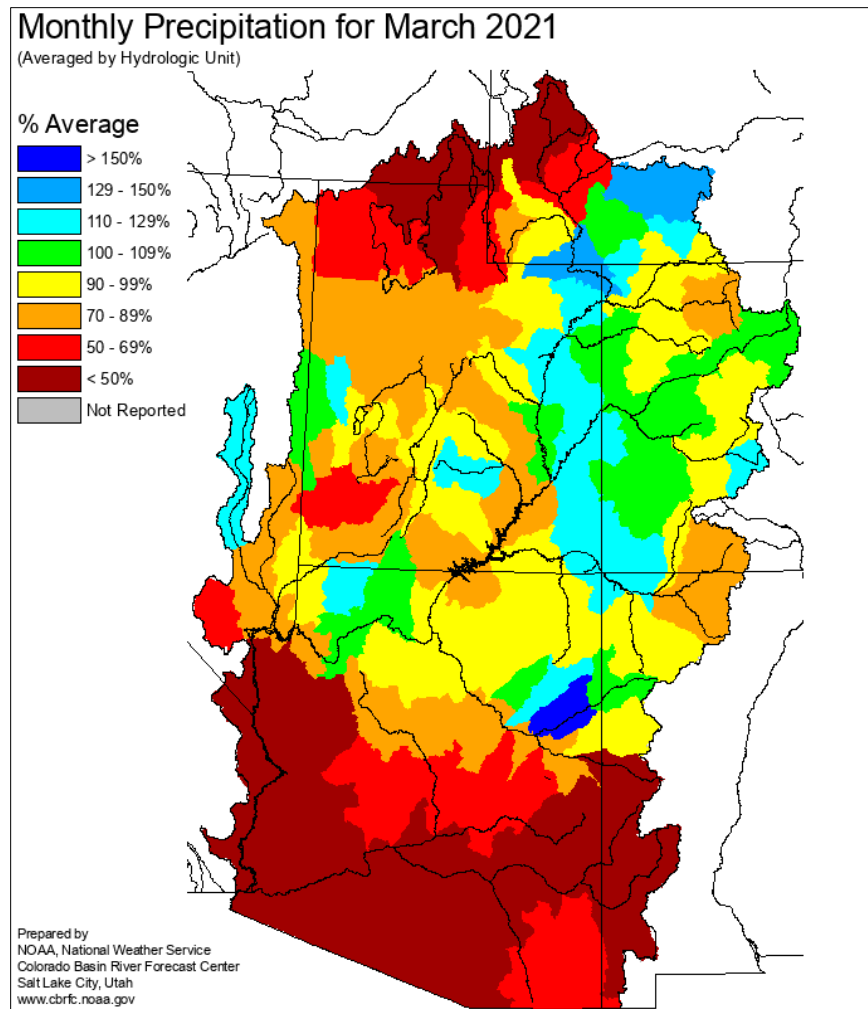


Figure 4.8 March 2020 precipitation, percent of normal

By the end of the first week of March, a broad upper-level trough was in place over the northeastern Pacific Ocean and western U.S. with a series of disturbances embedded within the upper-level flow. One such disturbance in central Nevada on the afternoon of March 9th was pushing toward Utah and would interact with a stalled mid-level boundary extending southwest to northeast across the state. Initially, a dry low level airmass was in place and, as such, only virga was occurring with none of the precipitation reaching the ground but by late afternoon some snow began to reach the ground in and near the target area. Some CNG sites were activated late afternoon/early evening with mainly light snow continuing through the night and ending early in the morning on March 10th. Storm total SWE was low, only 0.10"-020".

A vigorous closed low was located over Arizona on the morning of March 16th, bringing northeasterly winds to the Western Uintas. Enough moisture was in place to allow for some upslope flow on the eastern side of the Western Uintas, and one site in the High Uintas program was activated for a few hours in the afternoon to target clouds/snow showers moving into the Western Uintas target area.

During the morning of March 20th, a cold front pushed into the Western Uintas accompanied by a broad band of precipitation. 700 mb temperatures initially around -3°C dropped to -8°C behind the front, with widespread upslope precipitation developing. CNG sites were activated as this band moved into the area, with additional sites activated later in the day within the northwest flow regime. Precipitation continued overnight into the morning hours of March 21st before tapering off, and sites were shut off. Storm total SWE for this event ranged from 0.50" to 1.50".

Another northeasterly flow event took place on March 23rd, with snow showers moving into the target area from Wyoming and the central High Uintas. One site upstream of the target area was activated around the noon hour and continued to run until early evening, when precipitation came to an end. Due to wind direction with this event, this was the only site suitable for operations.

On March 25th, a broad trough of low pressure moved from the Pacific Northwest moved into the Great Basin, with light snow falling from a higher cloud deck over the target area. 700 mb temperatures were ideal, around -8°C. South to southwesterly flow was producing some lower clouds but at least through late afternoon, most of the precipitation was falling from the higher cloud deck. Some sites were activated as the lower clouds gradually developed more liquid water. Light snow shower bands moved across the target area during the evening and overnight hours, and by morning the wind flow was northwesterly, with a few more sites activated. Snow showers gradually diminished by late afternoon and seeding operations ceased. Storm total SWE was in the 0.20"-0.40" range.

April 2021

At the request of the clients, an extension of the program was granted into April. Precipitation was below normal across the state. Four storm events affected the state during the month, three of which were seedable for the Western Uintas target area.

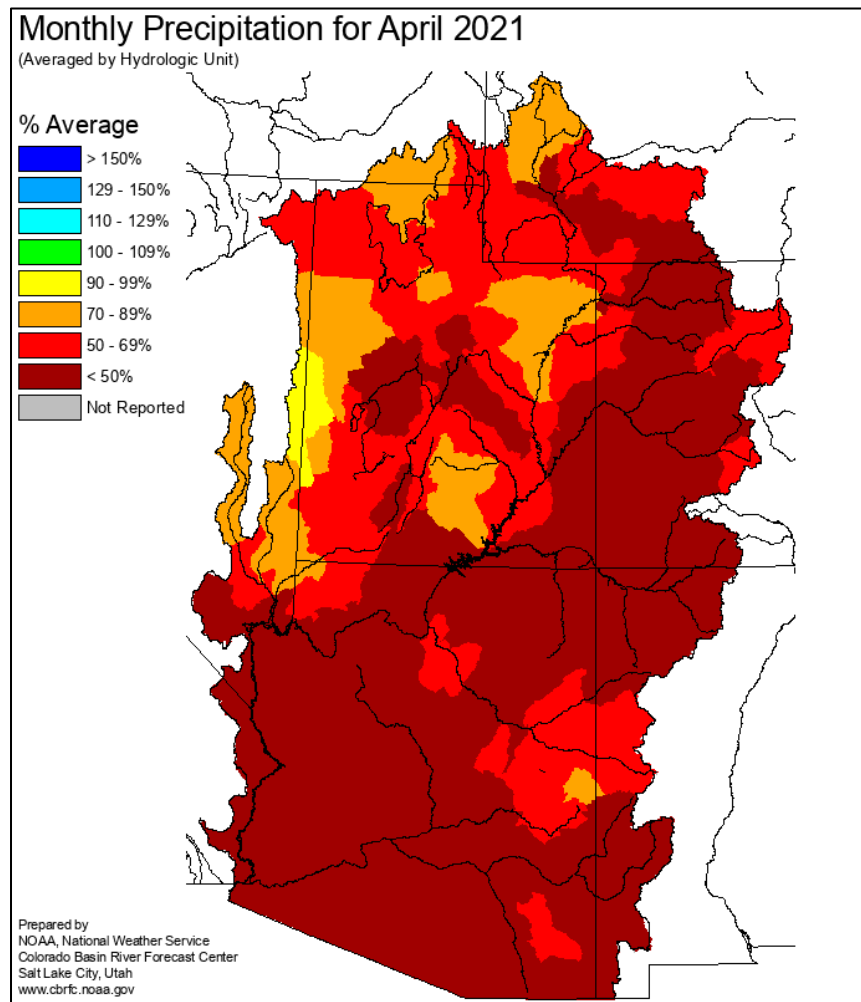


Figure 4.9 April 2020 precipitation, percent of normal

A large trough was in place over the Great Basin on April 14th. The airmass over Utah was dry despite the presence of some bands of snow showers over the northwestern quadrant of the state. Some of these bands expanded eastward into the Western Uintas by the noon hour and a couple of sites were activated as atmospheric conditions became more favorable for seeding. Snow showers continued until early evening before tapering off, at which time seeding operations came to an end. Storm total SWE ranged from 0.10"-0.50".

The aforementioned large trough had evolved into a closed upper low that was sitting over the state on April 15th. Extensive low clouds across the area within light north to northwest flow eventually began to produce light snow showers, and a few sites were activated shortly before noon. Seeding continued through the afternoon and overnight as snow showers continued, ending on the morning of the 16th. Storm total SWE ranged from 0.20" to 0.80".

A fast-moving trough of low pressure brought some snow showers to northern Utah on April 19th within strong northwest flow associated with a cold frontal passage. A couple of generator sites were activated for this event, which lasted into the overnight hours.

5.0 ASSESSMENT OF SEEDING EFFECTS

5.1 Background

The seemingly simple issue of determining the effects of cloud seeding has received considerable attention over the years. Evaluating the results of a cloud seeding program is often a rather difficult task, however, and the results, especially single-season indications, should be viewed with appropriate caution. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area. The ability to detect a seeding effect becomes a function of the size of the seeding increase relative to the natural variability in the precipitation pattern. Larger seeding effects can be detected more readily, and with a smaller number of seeded cases than are required to detect smaller increases.

Historically, among all cloud seeding project types, the most consistent results have been observed in wintertime seeding programs in mountainous areas, with results indicating 5-15 percent increases in seasonal precipitation. Establishing an accurate approximation of the effects of seeding within a single operational season can be challenging. Historically a rigorous study of seeding increase estimates required a multi-year randomized seeding evaluation. This multi-year assessment method made it impossible to address financial concerns in real time and encumbered projects with substantial operational limitations.

To provide our clients with greater decisioning power, we developed a mathematical evaluation process that enables us to perform single and multiple season evaluations. This model is based on a “target and control” comparison of a given variable that is affected by seeding (precipitation or snowpack) between a “target” area (where seeding occurred for the season being assessed) and a “control” area (where no seeding occurred for the season being assessed)

After identifying appropriate control sites, data for the selected variable (e.g., precipitation) is analyzed for both the “target” area and the “control” area **for years where no seeding was performed in either area**. A mathematical model (regression) is developed to determine the relationship between precipitation in the “target” area and precipitation in the “control” area under natural circumstances. This mathematical model is then used to analyze the selected variable in years where seeding **did not** occur in the “control” area but **did** occur in the “target” area. Using this model with data for the control sites, a reasonable prediction can be made of what would have transpired in the target area had no seeding occurred, then compare this to what actually happened in the target area. Consistent differences between the predicted and observed target area data may be attributed to cloud seeding effects, although with a low level of confidence until sufficient seeded season data is accumulated.

This target and control technique works well where good mathematical correlation can be found between target and control area precipitation. Generally, the closer the two areas are geographically, and the more similar they are in terms of elevation and topography, the higher the correlation and the more certain the results. Areas selected that are too close together, however, can be subject to contamination of the control sites by seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, a correlation coefficient (r) of 0.90 or better would be

considered excellent, and correlations around 0.85 would be very good. A correlation coefficient of 0.90 would indicate that over 80 percent of the variance (r^2) in the historical data set is explained by the regression equation used to estimate the subject variable (expected precipitation or snowpack) in the seeded years. Correlations less than about 0.80 are still acceptable, but it would likely take much longer to attach any statistical significance to the apparent results of seeding.

5.2 Considerations in the Development of Target/Control Evaluations

With the advent of the Natural Resources Conservation Service's (NRCS) SNOTEL automated data acquisition system in the late 1970's, access to precipitation and snowpack (water equivalent) data in mountainous locations became routine. Before the automated system was developed, these data had to be acquired by having NRCS personnel visit the site to take necessary measurements. This is still done at some sites although most have been automated. Historically, Utah has had snowpack measurements taken at (usually) monthly intervals. Precipitation and snowpack data used in the analysis were obtained from the NRCS and/or from the National Climatic Data Center. The current season NRCS data are considered provisional and subject to quality control analysis by the NRCS.

There have been, and continue to be, multiple cloud seeding programs conducted in the State of Utah. As a consequence, potential control areas that are unaffected by cloud seeding are somewhat limited. This is complicated by the fact that the best correlated control sites are generally those closest to the target area, and SNOTEL measurement sites in Utah have likely been affected at some time by numerous historical and current seeding programs.

Our normal approach in selecting control sites for a new project includes looking for sites that will geographically bracket the intended target area. The reason for this approach is that we have observed that some winter seasons are dominated by a particular upper airflow pattern while other seasons are dominated by other flow patterns. These different upper airflow patterns and resultant storm tracks often result in heavier precipitation in one area versus the other. For example, a strong El Nino pattern may favor the production of heavy winter precipitation in the southwestern United States while a strong La Nina pattern may favor the production of below normal precipitation in the southwest. The inclusion of control sites at somewhat varying latitudes (north-south), helping to bracket the target area, may improve the estimation of natural target area precipitation under variable upper airflow patterns.

Another consideration in the selection of control sites for the development of an historical target/control relationship is one of data quality. A potential control site may be rejected due to poor data quality if the data significantly diverges over time from other sites in the area. SNOTEL sites, the type used in the evaluation of the Western Uintas program, typically have reliable long-term records with external variables (such as terrain aspect and surrounding vegetation) carefully selected or maintained.

5.3 Evaluation of Snow Water Content

Historically, the Soil Conservation Service (SCS) routinely measured the mountain snowpack at snow courses once or twice per month, usually starting in January and continuing until May or June. Measurements were made by visiting the snow course (commonly a group of ten measurement points) and taking core samples of the snow to determine the water content and depth of the snow at each designated location along the course. Though this manual method is still being used at some sites,

beginning in the 1980s, the NRCS (formerly the SCS) automated SNOTEL system has provided daily measurements of snow water (and precipitation) at many of the mountain sites. With the use of a snow pillow, the water equivalent of the snowpack can be determined remotely by reading the weight of the snow on the snow pillow. The water content within the snowpack is important since, after consideration of antecedent soil moisture conditions, it ultimately determines how much water will be available as runoff when the snow melt occurs. Hydrologists routinely use snow water content to make forecasts of streamflow during the spring and early summer months. As with the precipitation storage gauge and SNOTEL precipitation gauge networks, Utah also has access to an excellent snow course and SNOTEL snow pillow reporting system via the NRCS. Many of the same reporting mountain sites are configured with collocated precipitation and snowpack measurements. Consequently, it was judged important to evaluate the effects of seeding on snowpack as well.

There are some potential pitfalls with snowpack measurements that must be recognized when using snow water content to evaluate seeding effectiveness. One problem that can occur is that not all winter storms are cold, and sometimes rain as well as snow falls in the mountains. This can lead to a disparity between precipitation totals (which measure everything that falls) and snowpack water content (which measures only the water held in the snowpack at a particular time). Also, warm periods can occur between snowstorms particularly in the spring season. If a significant warm period occurs, some of the precipitation that fell as snow may melt or sublimate by the time the next snow course measurement is made. This can also lead to a greater disparity between snow water content and precipitation at lower elevations (where more snow will melt in warm weather) than at higher elevations.

Another factor that can have an effect on the indicated results of the snowpack evaluation is the date on which the snowpack measurement was made. These measurements are generally made near the end of the month at the snow course sites and, since the advent of SNOTEL, are now made daily where possible. Prior to SNOTEL, and at those sites where snow courses are still measured by visiting the site, the measurement is recorded on the day it was made. In some cases, because of scheduling issues or stormy weather, the manual snow course measurements may have been made as much as several days before or after the end of the month. This can lead to a disparity in the snowpack water content readings when comparing one group (such as a control) with another control or target group. Normally, however, snowpack measurements are made within a few days of the intended date.

April 1st snowpack readings are widely used for runoff forecasting since they usually closely represent the maximum snow accumulation for the winter season. Most streamflow and reservoir storage forecasts are made on the basis of the April 1st snowpack data. For that reason, and because three to four months of seeding are generally represented in the April 1st snowpack measurements, April 1st was selected as the date for our snowpack analyses.

5.3.1 Target/Control Sites and Regression Equation Development

The procedure was essentially the same as what was done for the precipitation evaluation, e.g., control and target area sites were selected, and average values for each were determined. Seven target area snow measurement sites were utilized for the Western Uintas Program, as shown in Figure 5.1. Table 5-1 provides the target area site names, elevations and locations of these sites. The average elevation of the target sites is 8,637 feet MSL.

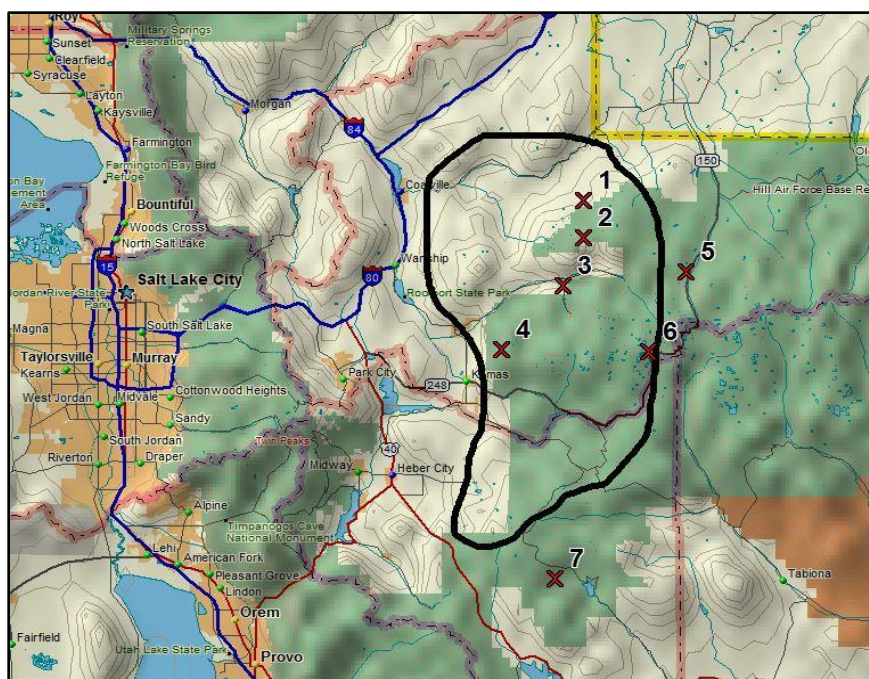


Figure 5.1 Western Uintas target area and snowpack target sites

Table 5-1
Target area snowpack sites

Map Label	Site Name	Elev. (Ft)	Lat. (N)	Long. (W)
1	Chalk Creek #2	8,200	40° 54'	111° 04'
2	Chalk Creek #1	9,100	40° 51'	111° 04'
3	Smith & Morehouse	7,600	40° 47'	111° 06'
4	Redden Mine, Lower	8,500	40° 41'	111° 13'
5	Hayden Fork	9,100	40° 48'	110° 53'
6	Trial Lake	9,960	40° 41'	110° 57'
7	Currant Creek	8,000	40° 21'	111° 05'

The five control sites are located in southern Idaho, northeastern Nevada and central Utah as shown in Figure 5.2. Control area site names, elevations and locations are provided in Table 5-2. The elevations of the control area sites average 6,887 feet (MSL). The non-seeded seasons were 1970-1988 and 1997-2000 (a total of 23 seasons). **Many more historical seasons were available for the snow water content analyses than for precipitation data, 23 versus 11 seasons. As a consequence, the snow water content analyses results are likely to be much more reliable than the precipitation analyses for this particular seeding program, and are the focus of this evaluation section.**

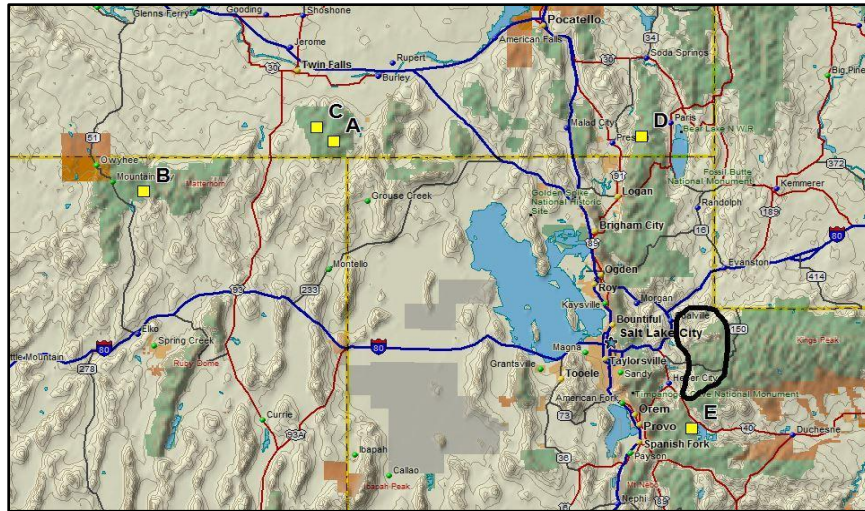


Figure 5.2 Western Uintas target area and snow control sites (squares)

Table 5-2
Control area snowpack sites

Map Label	Site Name	Site ID	Elev. (Ft)	Lat. (N)	Long. (W)
A	Badger Gulch SC, ID	14G03	6,660	42°06'	114°10'
B	Big Bend, NV	15H04S	6,700	41°46'	115°43'
C	Magic Mountain, ID	14G02S	6,880	42°11'	114°18'
D	Willow Flat SC, ID	11G04	6,070	42°08'	111°38'
E	Strawberry Divide, UT	11J08S	8,123	40°11'	111°13'

The linear regression equation developed from the historical relationship between the average control snowpack data and the average target snowpack data for April 1st was the following:

$$Y_C = 0.741 (X_O) + 6.36 \quad (4)$$

where Y_C is the calculated average snow water content (inches) for the seven-station target and X_O is the five-station control average observed snow water content for April 1st.

5.3.2 Linear Regression Snowpack Analysis

When the observed average control snow water content (11.5 inches) for April 1st, 2020 period was inserted in equation (1), the most probable average target area snow water content was calculated to be 14.9 inches. The actual observed average precipitation for the target group was 12.3 inches. This yields a single-season ratio of 0.82, which (for this single season) is itself not indicative of a seeding effect.

As stated before, the single-season evaluation results carry very little statistical significance. The strength of the evaluation lies in the multi-year results as shown below.

The combined (24-year) snow water linear regression evaluation for April 1st, for the Western Uintas target sites, yields a ratio of 1.03. This long-term mean excludes water years 2004 and 2015 during which abnormal early snowmelt occurred, and thus includes 24 seeded seasons. The implied 3% increase based on the snowpack evaluation is equivalent to an average of about 0.4 inches more water over the watersheds than might have occurred without the cloud seeding. The snowpack evaluation for the seeded water years is summarized in Table 5-3.

Table 5-3
Summary of April 1st snow water content evaluation,
using the Linear Regression technique.
Snowpack units are in inches of water equivalent.

Water Year	Control Average	Target Observed	Target Predicted	Obs/Pred Ratio	Excess Water (inches)
1989	17.22	18.04	19.12	0.94	-1.08
1990	6.94	14.79	11.50	1.29	3.28
1991	10.34	15.00	14.02	1.07	0.98
1992	3.44	10.29	8.91	1.15	1.38
1993	16.02	21.34	18.23	1.17	3.11
1995	11.96	18.43	15.22	1.21	3.21
2001	6.62	10.53	11.27	0.93	-0.74
2002	14.86	14.21	17.37	0.82	-3.16
2003	7.04	12.31	11.58	1.06	0.74
2005	14.26	21.09	16.93	1.25	4.16
2006	21.12	21.81	22.01	0.99	-0.20
2007	7.12	10.16	11.64	0.87	-1.48
2008	17.28	20.07	19.16	1.05	0.91
2009	14.06	17.17	16.78	1.02	0.39
2010	11.22	11.84	14.67	0.81	-2.83
2011	20.06	24.50	21.22	1.15	3.28
2013	9.14	10.69	13.13	0.81	-2.45
2014	11.16	16.61	14.63	1.14	1.98
2016	14.74	14.71	17.28	0.85	-2.57
2017	16.68	23.46	18.72	1.25	4.74
2018	7.40	10.29	11.84	0.87	-1.56
2019	18.44	21.64	20.02	1.08	1.62
2020	14.78	16.80	17.31	0.97	-0.51
2021	11.54	12.30	14.91	0.82	-2.61
24 years	12.64	16.16	15.73	1.03	0.43

5.3.3 Multiple Linear Regression Snowpack Analysis

A multiple linear regression analysis has been conducted for snowpack, and exhibits much lower seasonal variability in the indicated observed/predicted ratios than does the corresponding linear

regression. The r value is also much better than for the standard linear regression (0.90 vs. 0.79). This implies less background noise in this equation, and thus likely more reliable estimates of the true seeding effects. The results of the multiple regression snowpack analyses are provided in Table 5-4, implying about a 6% increase over the long term (obtained from the ratio of 1.06 shown in bold in the bottom row of that table). In the case of the Western Uintas evaluations, the multiple linear snowpack analysis is by far the strongest mathematically and is likely the most reliable for evaluation of this program.

A double ratio analysis using snowpack data (similar to that for precipitation) resulted in a ratio of 1.13, implying a 13% increase in the target area (relative to the control) during the seeded seasons. However, this result is a high outlier in these evaluations and may not be representative of the actual seeding effects. NAWC's best estimate of seeding effects for the Western Uintas program is about a 6% increase, as obtained in the multiple linear regression snowpack analysis.

Table 5-4
Summary of snow water content evaluation using the multiple linear regression technique.
Snowpack units are inches of water equivalent.

Water Year	Magic Mtn, ID	Badger Gulch, ID	Willow Flat, ID	Big Bend, NV	Strawberry Div, UT	Target Observed	Est Target Snow	Obs/Predicted Ratio	Excess Water (inches)
1989	23.60	16.20	18.00	10.50	17.80	18.04	17.84	1.01	0.20
1990	10.20	7.70	4.00	0.00	12.80	14.79	13.45	1.10	1.34
1991	14.70	7.50	11.20	2.40	15.90	15.00	14.95	1.00	0.05
1992	3.60	3.00	3.70	0.00	6.90	10.29	9.05	1.14	1.24
1993	18.10	14.60	17.70	8.40	21.30	21.34	20.18	1.06	1.16
1995	15.70	10.40	12.90	3.90	16.90	18.43	16.52	1.12	1.91
2001	11.40	6.10	5.10	2.00	8.50	10.53	10.02	1.05	0.51
2002	20.90	15.80	14.30	10.40	12.90	14.21	14.88	0.96	-0.66
2003	10.60	4.20	8.10	2.00	10.30	12.31	10.71	1.15	1.61
2005	16.70	9.80	14.90	7.70	22.20	21.09	18.68	1.13	2.40
2006	28.20	18.20	21.00	14.50	23.70	21.81	21.03	1.04	0.78
2007	14.00	5.20	6.00	1.80	8.60	10.16	9.51	1.07	0.65
2008	20.00	16.80	19.00	11.60	19.00	20.07	19.16	1.05	0.91
2009	20.40	10.20	15.50	10.10	14.10	17.17	13.50	1.27	3.67
2010	15.70	11.20	10.80	8.40	10.00	11.84	11.97	0.99	-0.13
2011	21.80	15.40	24.60	13.80	24.70	24.50	21.82	1.12	2.68
2013	15.20	9.60	9.40	2.00	9.50	10.69	12.03	0.89	-1.34
2014	17.70	11.40	10.20	2.20	14.30	16.61	15.18	1.09	1.43
2016	22.40	14.70	14.80	9.50	12.30	14.71	14.11	1.04	0.61
2017	19.80	15.10	15.20	10.10	23.20	23.46	20.64	1.14	2.82
2018	12.70	6.90	7.10	2.70	7.60	10.29	9.79	1.05	0.49
2019	21.20	17.70	19.00	10.40	23.90	21.64	22.32	0.97	-0.67
2020	21.40	15.60	13.00	8.40	15.50	16.80	16.37	1.03	0.43
2021	16.60	12.40	12.00	6.70	10.00	12.30	12.78	0.96	-0.48
24 yrs	17.19	11.49	12.81	6.65	15.08	16.16	15.27	1.06	0.89

5.4 Summary of Evaluation Results

The April 1st **snowpack** analyses for 24 seeded seasons (2004 and 2015 were excluded) yield observed/predicted ratios of 1.03 (linear) and 1.06 (multiple linear). The results using April 1st snowpack imply average increases of roughly 3%-6%, which seems reasonable for this program, particularly in comparison to results of similar programs in the western U.S. and nearby programs in Utah. The April 1st snowpack evaluations are considered much more representative than the December-March precipitation evaluation (previously included in this section) due to a much longer historical period being available for the snow water versus precipitation evaluation of 23 versus 11 seasons, and a stronger statistical correlation (i.e., r value of 0.90). Also of interest in the case of the snowpack evaluations is the much lower year-to-year variability observed in the results of the snowpack multiple linear evaluation, suggesting that this particular equation is likely the best predictor of the “expected” natural target area precipitation based on the available control site snowpack data. **This suggests a likely long-term average seeding effect in the neighborhood of 6% for this program.**

NAWC considers the Western Uintas evaluations to be conservative estimates of the effects of seeding for a variety of reasons. For example, some months that were included in the “seeded” period actually were not seeded during all seasons. Also, one of the control sites (Strawberry Divide) is located in an area that has been seeded for another program during some winter seasons. The snowpack evaluations are also conservative because they are based upon April 1st data. These data contain periods in the fall and early winter in which snowpack accumulated in the target area without any effects of seeding. This would dilute the indicated effects of seeding over the long term.

Due in large part to the continually rising demand for water across the Rocky Mountain States, there are no longer any particularly good control sites. The few potential sites that reside close to the target area and have adequate historic records are all likely affected by other nearby cloud-seeding projects each winter, thus reducing the apparent gains derived from cloud seeding

Another potential confounding issue in evaluating the effects of cloud seeding in the Western Uintas target area is that the historical target/control evaluations seem to be impacted by urban air pollution, based upon an analysis performed and published by NAWC (Griffith et al., 2005). A copy of the paper on this topic was provided in the 2005 report and is also available on NAWC’s website (www.nawcinc.com/nawcpapers.html). **That analysis documented an approximate 16% decline in the November through March precipitation at Trial Lake during the period from 1956 to 2004.** Data more recent than this would be affected by cloud seeding as well, with the competing effects difficult to separate.

The control area sites in northeastern Nevada and southwestern Idaho are primarily in unpopulated areas which would not be expected to be subject to the air pollution problems as discussed in the 2005 paper. On the other hand, from our investigations (Griffith et al., 2005) it appears that some of the target sites for the Western Uintas program are being negatively impacted by air pollution. The likely result then is that the equations used to evaluate the program may be over-predicting the amount of “natural” precipitation (i.e., that which would occur without seeding) in the target area during the seeded periods. As a consequence, the evaluations of the program are likely indicating less of a seeding effect than is actually occurring.

This situation was also considered in a study conducted by Givati and Rosenfeld (2004); they reported on an operational cloud seeding program being conducted in Israel, plus some areas in California that are exhibiting these pollution impacts. A quote from the Givati and Rosenfeld study is as follows: "In this study, we avoided addressing the possible confounding effects of the glaciogenic cloud seeding of the orographic clouds in both Israel and California. If seeding did enhance precipitation, the effects in the absence of seeding may have been larger than indicated in this study." **In other words, cloud seeding may potentially be offsetting the negative effects of air pollution on precipitation.** For example, if air pollution was reducing December through March precipitation by 10% and cloud seeding was increasing precipitation by 10%, the evaluations that we have been conducting for the Western Uintas may indicate no effect even though there actually was a 10% increase due to cloud seeding. And the corollary is that without cloud seeding, the drop in precipitation due to pollution effects might be more pronounced.

Appendix C contains additional information on the historical and seeded years precipitation and snow water averages, regression equations and predicted and observed values.

6.0 CONCLUSIONS

The difficulties involved in predicting seasonal increases in snowpack resulting from cloud seeding have been thoroughly described in this report. With those realities and their potential impacts summarized, we offer the following statements regarding the seeding project effectiveness.

The cumulative evaluation results using the regular and multiple linear regression techniques based on April 1st snow water content, indicate an estimated 3% to 6% seasonal average increase. These are considered to be the best, most credible (although perhaps still conservative) estimations of the true effects of the seeding program.

For the Western Uintas program, a 5% average increase would yield approximately ~0.8 inches of additional water over the target area. The target area comprises approximately 600 square miles. An average 0.8 inches of augmented water across the target would yield approximately 25,000 additional acre-feet of runoff. Using an estimated average current cost of conducting the seeding program, the cost of producing the additional runoff via cloud seeding is approximately \$3.01 per acre-foot.

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APPENDIX A SUSPENSION CRITERIA

Certain situations require temporary or longer-term suspension of cloud seeding activities, with reference to well-considered criteria for consideration of possible suspensions, to minimize either an actual or apparent contribution of seeding to a potentially hazardous situation. The ability to forecast (anticipate) and judiciously avoid hazardous conditions is very important in limiting any potential liability associated with weather modification and to maintain a positive public image.

There are three primary hazardous situations around which suspension criteria have been developed. These are:

1. Excess snowpack accumulation
2. Rain-induced winter flooding
3. Severe weather

1. Excess Snowpack Accumulation

Snowpack begins to accumulate in the mountainous areas of Utah in November and continues through April. The heaviest average accumulations normally occur from January through March. Excessive snowpack water content becomes a potential hazard during the resultant snowmelt. The Natural Resources Conservation Service (NRCS) maintains a network of high elevation snowpack measurement sites in the State of Utah, known as the SNOTEL network. SNOTEL automated observations are now readily available, updated as often as hourly. The following set of criteria, based upon observations from these SNOTEL site observations, has been developed as a guide for potential suspension of operations.

Project & Basin	Critical Streamflow Volume (Acft) & USGS Streamgage	SNOTEL Station	SWE Value Corresponding to the Critical Flow								Ranking of SNOTEL Stations
			Jan 1 (in.)	Jan 1 (%)	Feb 1 (in.)	Feb 1 (in. %)	March 1 (in.)	March 1 (in. %)	April 1 (in.)	April 1 (in. %)	
1. Northern Utah <i>Logan at Logan</i>	185,208	Franklin Basin, Idaho	19.50	190.84	27.14	165.31	34.35	154.71	41.56	153.60	1
	USGS 10109000	Tony Grove	28.73	205.94	39.44	175.56	48.06	160.38	56.34	156.56	2
		Bug Lake	17.08	218.82	21.91	180.34	163.25	163.25	31.65	162.70	3
Weber near Oakley		Average	21.80	205.20	29.50	173.70	36.40	160.10	43.20	157.60	
	176,179	Chalk Creek #1	10.09	173.13	14.73	153.66	28.77	149.85	34.15	143.41	1
	USGS 10128500	Trail Lake	20.15	207.44	26.33	180.55	33.55	173.27	38.54	162.28	2
		Smith Morehouse	10.06	186.34	13.49	137.60	17.36	146.32	21.17	160.26	3
		Hayden Fork	12.19	194.16	16.69	172.11	20.71	158.56	21.79	164.64	4
Dunn Creek near the Park Valley		Average	13.10	190.30	17.90	166.00	25.10	157.10	28.90	157.70	
	5,733	George Creek	17.84	187.75	18.32	143.81	28.93	163.43	34.61	153.77	1
	USGS 1012952	Howell Canyon, Idaho	28.71	279.96	38	223.24	44.59	205.98	50.46	191.65	2
2. Western & High Uintah <i>Bear River near Utah - Wyoming state line</i>		Average	23.30	233.90	28.20	183.60	36.80	184.70	42.60	172.70	
	166,861	Lily Lake	11.38	202.70	16.40	194.06	17.69	147.37	28.93	139.19	1
	USGS 10011500	Trail Lake	20.07	206.54	26.56	182.26	33.68	173.94	38.49	162.05	2
		Hayden Fork	12.41	197.65	17.06	175.83	21.03	160.98	20.90	146.02	3
		Average	14.60	202.30	20.00	184.10	24.10	160.80	29.40	149.10	
Duchesne near Tablona	140,976	Strawberry Divide	6.92	229.23	10.87	199.25	26.77	178.78	29.75	179.05	1
	USGS 09277500	Daniel's Strawberry	16.07	248.12	21.50	202.44	27.82	190.54	29.80	197.75	2
		Smith Morehouse	10.61	196.64	14.95	172.41	18.82	158.83	22.22	168.26	3
Provo near woodland		Rock Creek	8.76	230.02	12.31	219.65	15.88	205.68	16.41	209.06	4
		Average	10.60	228.50	14.90	198.50	22.30	183.50	24.60	187.30	
	183,845	Trail Lake	22.98	226.33	27.78	190.63	35.23	181.59	31.44	132.39	1
	USGS 09277500	Beaver Divide	10.29	210.39	14.11	179.49	17.45	170.83	20.18	200.3	2
		Average	16.70	223.50	20.90	185.10	26.50	176.20	25.80	166.40	
3. Central & Southern <i>Sewer near Hatch</i>	120,473	Castle Valley	12.23	244.05	16.96	203.04	22.22	187.68	26.30	180.00	1
	USGS 10174500	Harris Flat	8.71	298.76	15.25	273.59	24.16	222.99	21.15	209.77	2
		Farnsworth Lake	17.35	218.10	20.96	185.95	27.05	182.24	32.93	167.03	3
		Average	12.80	253.70	17.70	220.90	24.50	197.70	26.80	185.60	
	38,533	Midway Valley	20.89	215.65	29.12	194.04	35.89	176.99	42.29	167.97	1
Coal Creek near Cedar City	USGS 10242000	Webster Flat	13.57	252.46	18.70	197.95	24.30	184.64	24.93	181.12	2
		Average	17.20	224.10	23.90	196.00	30.10	180.90	33.60	174.60	
	3,426	Rocky Basin-settlement	19.09	205.33	23.75	174.14	32.11	171.39	40.01	167.51	1
South Willow near Grantsville	USGS 10172800	Nutting Fork	16.31	243.60	20.74	177.04	27.81	171.79	32.19	168.74	2
		Average	17.70	224.50	22.30	175.60	30.00	171.60	36.10	168.10	
	151,286	Kolob	23.11	229.25	29.98	220.78	36.51	197.43	43.71	196.21	1
	USGS 09406000	Harris Flat	9.71	377.00	15.69	304.18	21.46	300.00	20.11	370.00	2
		Midway Valley	24.76	256.17	34.56	238.40	41.44	209.68	51.03	211.06	3
Virgin River at Virgin		Long Flat	9.38	265.88	13.54	286.16	19.20	286.18	18.91	187.00	4
		Average	16.70	282.10	23.20	262.40	29.70	248.40	33.40	241.00	
	11,620	Gardner Peak	13.00	293.90	16.82	172.15	21.70	167.36	24.45	163.95	1
	USGS 09409100	Average	13.00	293.90	16.80	172.10	21.70	167.40	24.50	164.00	
		Utah State Average (%)		230		197		183		178	
Santa Clara above Baker Reservoir		Standard Deviation		42		38		35		42	
		Upper 95%		248		213		199		196	
		Lower 95%		212		180		168		160	

Snowpack-related suspension considerations will be assessed on a geographical division or sub-division basis. The NRCS has divided the State of Utah into 13 such divisions as follows: Bear River, Weber-Ogden Rivers, Provo River-Utah Lake-Jordan River, Tooele Valley-Vernon Creek, Green River, Duchesne

River, Price-San Rafael, Dirty Devil, South Eastern Utah, Sevier River, Beaver River, Escalante River, and Virgin River. The Weber-Ogden and Provo River – Utah Lake – Jordan River criteria apply to suspension considerations for the Western Uintas project. Since SNOTEL observations are available on a daily basis, suspensions (and cancellation of suspensions) can be made on a daily basis using linear interpolation of the first of month criteria. For the Western Uintas, four SNOTEL sites (Chalk Creek #1, Trial Lake, Smith and Morehouse, and Rock Creek) have date-specific snow water equivalent criteria on which suspension decisions can be based.

Streamflow forecasts, reservoir storage levels, soil moisture content and amounts of precipitation in prior seasons are other factors which need to be considered when the potential for suspending seeding operations due to excess snowpack water content exists.

2. Rain-induced Winter Floods

The potential for wintertime flooding from rainfall on low elevation snowpack is fairly high in some (especially the more southern) target areas during the late winter/early spring period. Every precaution must be taken to insure accurate forecasting and timely suspension of operations during these potential flood-producing situations. The objective of suspension under these conditions is to eliminate both the real and/or perceived impact of weather modification when any increase in precipitation has the potential of creating a flood hazard.

3. Severe Weather

During periods of hazardous weather associated with both winter orographic and convective precipitation systems it is sometimes necessary or advisable for the National Weather Service (NWS) to issue special weather bulletins advising the public of the weather phenomena and the attendant hazards. Each phenomenon is described in terms of criteria used by the NWS in issuing special weather bulletins. Those that may be relevant in the conduct of winter cloud seeding programs include the following:

- **Winter Storm Warning** - This is issued by the NWS when it expects heavy snow warning criteria to be met, along with strong winds/wind chill or freezing precipitation.
- **Flash Flood Warnings** - This is issued by the NWS when flash flooding is imminent or in progress. In the Intermountain West, these warnings are generally issued relative to, but are not limited to, fall or spring convective systems.

Seeding operations may be suspended whenever the NWS issues a weather warning for or adjacent to any target area. Since the objective of the cloud seeding program is to increase winter snowfall in the mountainous areas of the state, operations will typically not be suspended when Winter Storm Warnings are issued, unless there are special considerations (e.g., a heavy storm that impacts Christmas Eve travel).

Flash Flood Warnings are usually issued when intense convective activity causing heavy rainfall is expected or is occurring. Although the probability of this situation occurring during our core operational seeding periods is low, the potential does exist, especially over southern sections of the state during late March and early April, which can include the project spring extension period. The type of storm that may cause problems is one that has the potential of producing 1-2 inches (or greater) of rainfall in

approximately a 24-hour period, combined with high freezing levels (e.g., > 8,000 feet MSL). Seeding operations will be suspended for the duration of the warning period in the affected areas.

NAWC's project meteorologists have the authority to temporarily suspend localized seeding operations due to development of hazardous severe weather conditions even if the NWS has not issued a warning. This would be a rare event, but it is important for the operator to have this latitude.

APPENDIX B SEEDING OPERATIONS TABLES

Table B-1
Generator Hours – Western Uintas, 2020-2021
Storms 1-10 (rounded to quarter hour)

Storm	1	2	3	4	5	6	7	8	9	10
Date	Dec 12	Dec 17-18	Dec 22-23	Jan 4-5	Jan 22-23	Jan 29-30	Feb 3	Feb 5	Feb 13-14	Feb 15-16
SITE										
W1										
W2		11								
W3	5.75							9.75	14.25	19.75
W4	5.75	12.5					9	10.25	11	
W6		11.5	15.5		20	13	8.5	10	22	
W7		13.75	18		20	13	9	10		18.75
W8		11.5				13	9	10	19.5	19.75
W9		12.5	16.5	12	21	13	8.75	10	22.25	20
W10	5.5	13	17	12	21	13	9	9.5	22.25	
W11		9.5	14.25	12	20.5	12	9.5		8.75	19.75
W12		12.25	16	12		14	8.75		22.25	
W14		12	16		20.25	13	10	10.75	22	
Storm Total	17	119.5	113.25	48	122.75	104	81.5	80.25	164.25	98

Table B-2
Generator Hours – Western Uintas, 2020-2021
Storms 11-19

Storm	11	12	13	14	15	16	17	18	19	
Date	Feb 26-27	Mar 9-10	Mar 16	Mar 20-21	Mar 23	Mar 25-26	Apr 14	Apr 15-16	Apr 19	Site Totals
SITE										
W1										0
W2				12.25						23.25
W3	13	14.25		12.25		8.75		5.5	5	108.25
W4		13		12		8.75		20.25		102.5
W6	13	14.25		21.25						149
W7	13			21			6.75			143.25
W8	13	14		21						130.75
W9	13			21.25		6.25	6.5			183
W10	13	14					7			156.25
W11	13									119.25
W12		14.25				4.5				104
W14	14	14		19.75					3	154.75
H18*			3		6.75			5		9.75
Storm Total	105	97.75	3	140.75	6.75	28.5	20.25	30.75	8.00	1272.75

* A site designated for the High Uintas program that was used to seed the Western Uintas in certain wind flow situations

APPENDIX C EVALUATION DATA

Western Uintas December – March Precipitation, Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:					
1980	21.45	19.89	17.93	1.11	1.96
1981	9.55	11.53	9.90	1.16	1.63
1982	21.23	20.44	17.78	1.15	2.66
1983	16.45	13.03	14.56	0.90	-1.53
1984	20.43	13.81	17.24	0.80	-3.42
1985	9.63	11.47	9.95	1.15	1.52
1986	18.55	17.23	15.97	1.08	1.26
1987	8.73	8.41	9.34	0.90	-0.93
1988	10.88	10.77	10.79	1.00	-0.02
1997	20.68	17.74	17.41	1.02	0.34
1998	16.48	14.34	14.57	0.98	-0.23
1999	14.25	12.64	13.07	0.97	-0.43
2000	15.15	14.47	13.68	1.06	0.79
Mean	15.68	14.03	14.03	1.00	0.00

Seeded period:					
YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	15.03	13.37	13.60	0.98	-0.23
1990	9.85	11.59	10.10	1.15	1.48
1991	10.00	11.46	10.20	1.12	1.25
1992	5.15	6.01	6.93	0.87	-0.92
1993	17.13	17.83	15.01	1.19	2.82
1994*	9.15	10.71	9.63	1.11	1.08
1995	12.45	14.71	11.86	1.24	2.86
1996*	18.73	18.37	16.09	1.14	2.28
2001	9.23	8.64	9.68	0.89	-1.04
2002	13.45	10.37	12.53	0.83	-2.16
2003	9.93	9.61	10.15	0.95	-0.54
2004	14.58	10.36	13.29	0.78	-2.93
2005	11.60	14.99	11.28	1.33	3.70
2006**	21.43	16.99	17.91	0.95	-0.93
2007**	12.23	9.29	11.71	0.79	-2.42
2008**	16.93	16.54	14.88	1.11	1.67
2009**	16.20	14.67	14.39	1.02	0.28
2010**	12.13	9.41	11.64	0.81	-2.22
2011**	17.43	17.91	15.21	1.18	2.70
2012*	11.78	8.47	11.40	0.74	-2.93
2013	13.35	9.03	12.46	0.72	-3.44
2014	14.48	13.20	13.22	1.00	-0.02

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
2015	11.08	7.99	10.93	0.73	-2.94
2016	17.80	13.16	15.47	0.85	-2.31
2017	21.30	23.00	17.83	1.29	5.17
2018	11.63	8.80	11.30	0.78	-2.50
2019	15.33	14.97	13.80	1.09	1.17
2020	15.20	12.60	13.71	0.92	-1.11
2021	11.73	9.77	11.37	0.86	-1.60
Mean	13.71	12.55	12.71	0.99	-0.16

* No seeding in target areas

** Seeding in Weber Basin but not in Provo R Basin

SUMMARY OUTPUT

<i>Regression Statistics</i>	
Multiple R	0.877723
R Square	0.770398
Adjusted R Square	0.744887
Standard Error	1.728461
Observations	11

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	3.456066	1.994168	1.733087	0.117116	-1.05506
X Variable 1	0.674813	0.122798	5.495294	0.000383	0.397024

Western Uintas April 1 Snowpack, Linear Regression

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
Regression (non-seeded) period:					
1970	16.14	16.21	18.32	0.89	-2.11
1971	18.66	21.43	20.19	1.06	1.24
1972	19.18	18.17	20.57	0.88	-2.40

1973	16.02	16.61	18.23	0.91	-1.62
1974	18.42	16.77	20.01	0.84	-3.24
1975	20.08	19.97	21.24	0.94	-1.27
1976	17.46	17.33	19.30	0.90	-1.97
1977	6.24	8.97	10.98	0.82	-2.01
1978	16.18	19.23	18.35	1.05	0.88
1979	17.40	17.80	19.25	0.92	-1.45
1980	19.86	25.26	21.08	1.20	4.18
1981	8.38	12.66	12.57	1.01	0.09
1982	21.08	23.50	21.98	1.07	1.52
1983	18.42	20.90	20.01	1.04	0.89
1984	24.80	22.01	24.74	0.89	-2.72
1985	16.06	21.44	18.26	1.17	3.18
1986	15.84	25.73	18.10	1.42	7.63
1987	8.08	13.97	12.35	1.13	1.62
1988	11.42	14.23	14.82	0.96	-0.59
1997	19.72	22.41	20.97	1.07	1.44
1998	14.30	16.39	16.96	0.97	-0.57
1999	13.34	14.86	16.24	0.91	-1.39
2000	13.90	15.41	16.66	0.93	-1.25
Mean	16.13	18.32	18.31	1.00	0.00

Seeded period:

YEAR	XOBS	YOBS	YCALC	RATIO	EXCESS
1989	17.22	18.04	19.12	0.94	-1.08
1990	6.94	14.79	11.50	1.29	3.28
1991	10.34	15.00	14.02	1.07	0.98
1992	3.44	10.29	8.91	1.15	1.38
1993	16.02	21.34	18.23	1.17	3.11
1994*	8.42	13.31	12.60	1.06	0.72
1995	11.96	18.43	15.22	1.21	3.21
1996*	16.96	22.21	18.93	1.17	3.29
2001	6.62	10.53	11.27	0.93	-0.74
2002	14.86	14.21	17.37	0.82	-3.16
2003	7.04	12.31	11.58	1.06	0.74
2004***	11.74	9.83	15.06	0.65	-5.23
2005	14.26	21.09	16.93	1.25	4.16
2006**	21.12	21.81	22.01	0.99	-0.20
2007**	7.12	10.16	11.64	0.87	-1.48
2008**	17.28	20.07	19.16	1.05	0.91
2009**	14.06	17.17	16.78	1.02	0.39
2010**	11.22	11.84	14.67	0.81	-2.83
2011**	20.06	24.50	21.22	1.15	3.28
2012*	9.22	8.86	13.19	0.67	-4.33
2013	9.14	10.69	13.13	0.81	-2.45
2014	11.16	16.61	14.63	1.14	1.98
2015***	4.66	6.40	9.81	0.65	-3.41

2016	14.74	14.71	17.28	0.85	-2.57
2017	16.68	23.46	18.72	1.25	4.74
2018	7.40	10.29	11.84	0.87	-1.56
2019	18.44	21.64	20.02	1.08	1.62
2020	14.78	16.80	17.31	0.97	-0.51
2021	11.54	12.30	14.91	0.82	-2.61
Mean	12.64	16.16	15.73	1.027	0.43

* No seeding in target areas

** Seeding in Weber Basin only, not in Provo R Basin

*** Excluded from the mean due to excessive snow melt

SUMMARY OUTPUT

<i>Regression Statistics</i>	
Multiple R	0.790698
R Square	0.625203
Adjusted R Square	0.607356
Standard Error	2.604868
Observations	23

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>
Intercept	6.361749	2.091542	3.041654	0.006201	2.012148
X Variable 1	0.741148	0.125223	5.918647	7.11E-06	0.480734

Western Uintas April 1 Snowpack, Multiple Linear Regression

YEAR	Magic Mtn, ID	Badger Gulch, ID	Willow Flat, ID	Big Bend, NV	Strawberry Divide, UT	YOBS	YCALC	RATIO	EXCESS
Non-Seeded Years									
1970	23.30	15.30	13.10	10.80	18.20	16.21	17.11	0.95	-0.89
1971	24.80	14.10	20.40	12.70	21.30	21.43	18.69	1.15	2.74
1972	33.40	20.40	13.20	10.90	18.00	18.17	17.76	1.02	0.41
1973	21.60	14.40	15.40	8.90	19.80	16.61	18.45	0.90	-1.83
1974	25.20	20.00	17.00	11.90	18.00	16.77	18.95	0.88	-2.18
1975	24.40	18.70	20.40	15.70	21.20	19.97	20.06	1.00	-0.09
1976	22.00	15.50	21.20	12.70	15.90	17.33	16.71	1.04	0.62
1977	8.40	6.00	6.00	3.10	7.70	8.97	9.84	0.91	-0.87
1978	19.20	12.40	15.20	9.20	24.90	19.23	20.71	0.93	-1.48
1979	19.60	14.60	19.40	10.10	23.30	17.80	21.02	0.85	-3.22

1980	21.50	15.70	20.40	13.70	28.00	25.26	23.35	1.08	1.91
1981	12.00	7.20	6.60	2.00	14.10	12.66	13.70	0.92	-1.04
1982	28.10	18.20	19.30	13.70	26.10	23.50	22.32	1.05	1.18
1983	24.60	14.60	12.90	15.70	24.30	20.90	19.19	1.09	1.71
1984	32.00	19.50	25.10	18.00	29.40	22.01	24.14	0.91	-2.12
1985	20.80	14.70	15.40	9.10	20.30	21.44	18.92	1.13	2.52
1986	19.10	16.10	16.60	4.40	23.00	25.73	22.17	1.16	3.56
1987	10.60	8.80	6.90	2.30	11.80	13.97	13.24	1.06	0.73
1988	16.10	9.00	10.80	6.80	14.40	14.23	13.75	1.04	0.48
1997	26.90	18.60	17.40	8.40	27.30	22.41	23.99	0.93	-1.58
1998	18.20	11.50	16.00	7.20	18.60	16.39	17.39	0.94	-1.01
1999	20.00	13.80	13.40	8.00	11.50	14.86	13.69	1.08	1.16
2000	18.50	11.90	13.10	8.80	17.20	15.41	16.12	0.96	-0.71
Mean	21.32	14.39	15.44	9.74	19.75	18.32	18.32	1.00	0.00

Seeded Years

YEAR	Magic Mtn, ID	Badger Gulch, ID	Willow Flat, ID	Big Bend, NV	Strawberry Divide, UT	YOBS	YCALC	RATIO	EXCESS
1989	23.60	16.20	18.00	10.50	17.80	18.04	17.84	1.01	0.20
1990	10.20	7.70	4.00	0.00	12.80	14.79	13.45	1.10	1.34
1991	14.70	7.50	11.20	2.40	15.90	15.00	14.95	1.00	0.05
1992	3.60	3.00	3.70	0.00	6.90	10.29	9.05	1.14	1.24
1993	18.10	14.60	17.70	8.40	21.30	21.34	20.18	1.06	1.16
1994*	11.60	8.40	11.60	0.40	10.10	13.31	12.88	1.03	0.44
1995	15.70	10.40	12.90	3.90	16.90	18.43	16.52	1.12	1.91
1996*	21.20	14.70	16.30	10.20	22.40	22.21	19.96	1.11	2.25
2001	11.40	6.10	5.10	2.00	8.50	10.53	10.02	1.05	0.51
2002	20.90	15.80	14.30	10.40	12.90	14.21	14.88	0.96	-0.66
2003	10.60	4.20	8.10	2.00	10.30	12.31	10.71	1.15	1.61
2004***	20.20	13.00	11.40	3.60	10.50	9.83	13.30	0.74	-3.47
2005	16.70	9.80	14.90	7.70	22.20	21.09	18.68	1.13	2.40
2006**	28.20	18.20	21.00	14.50	23.70	21.81	21.03	1.04	0.78
2007**	14.00	5.20	6.00	1.80	8.60	10.16	9.51	1.07	0.65
2008**	20.00	16.80	19.00	11.60	19.00	20.07	19.16	1.05	0.91
2009**	20.40	10.20	15.50	10.10	14.10	17.17	13.50	1.27	3.67
2010**	15.70	11.20	10.80	8.40	10.00	11.84	11.97	0.99	-0.13
2011**	21.80	15.40	24.60	13.80	24.70	24.50	21.82	1.12	2.68
2012*	17.20	10.90	9.30	2.80	5.90	8.86	10.14	0.87	-1.29
2013	15.20	9.60	9.40	2.00	9.50	10.69	12.03	0.89	-1.34
2014	17.70	11.40	10.20	2.20	14.30	16.61	15.18	1.09	1.43
2015***	13.00	5.40	0.00	0.00	4.90	6.40	7.25	0.88	-0.85
2016	22.40	14.70	14.80	9.50	12.30	14.71	14.11	1.04	0.61
2017	19.80	15.10	15.20	10.10	23.20	23.46	20.64	1.14	2.82
2018	12.70	6.90	7.10	2.70	7.60	10.29	9.79	1.05	0.49
2019	21.20	17.70	19.00	10.40	23.90	21.64	22.32	0.97	-0.67
2020	21.40	15.60	13.00	8.40	15.50	16.80	16.37	1.03	0.43

2021	16.60	12.40	12.00	6.70	10.00	12.30	12.78	0.96	-0.48
Mean	17.19	11.49	12.81	6.65	15.08	16.16	15.27	1.058	0.89

* No seeding in target areas

** Seeding in Weber Basin only, not Provo River Basin

*** Excluded due to excessive snow melt

SUMMARY OUTPUT

Regression Statistics

Multiple R	0.90476
R Square	0.81859
Adjusted R Square	0.76523
Standard Error	2.01422
Observations	23

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	3.99574	1.84903	2.16099	0.04526	0.09463	7.89686	0.09463	7.89686
X Variable 1	-0.13065	0.21561	-0.6059	0.55256	-0.5855	0.32425	-0.5855	0.32425
X Variable 2	0.41099	0.30428	1.35067	0.19451	-0.231	1.05297	-0.231	1.05297
X Variable 3	0.11836	0.18066	0.65516	0.52114	-0.2628	0.49953	-0.2628	0.49953
X Variable 4	-0.17098	0.20373	-0.8392	0.41298	-0.6008	0.25886	-0.6008	0.25886
X Variable 5	0.55836	0.1195	4.67251	0.00022	0.30624	0.81048	0.30624	0.81048

APPENDIX D GLOSSARY

Advection: Movement of an air mass. Cold advection describes a colder air mass moving into the area, and warm advection is used to describe an incoming warmer air mass. Dry and moist advection can be used similarly.

Air Mass: A term used to describe a region of the atmosphere with certain defining characteristics. For example, a cold or warm air mass, or a wet or dry air mass. It is a fairly subjective term but is usually used in reference to large (synoptic scale) regions of the atmosphere, both near the surface and/or at mid and upper levels of the atmosphere.

Cold-core low: A typical mid-latitude type of low pressure system, where the core of the system is colder than its surroundings. This type of system is also defined by the cyclonic circulation being

strongest in the upper levels of the atmosphere. The opposite is a warm-core low, which typically occurs in the tropics.

Cold Pool: An air mass that is cold relative to its surroundings, and may be confined to a particular basin

Condensation: Phase change of water vapor into liquid form. This can occur on the surface of objects (such as dew on the grass) or in mid-air (leading to the formation of clouds). Clouds are technically composed of water in liquid form, not water vapor.

Confluent: Wind vectors coming closer together in a two-dimensional frame of reference (opposite of diffluent). The term convergence is also used similarly.

Convective (or convection): Pertains to the development of precipitation areas due to the rising of warmer, moist air through the surrounding air mass. The warmth and moisture contained in a given air mass makes it lighter than colder, dryer air. Convection often leads to small-scale, locally heavy showers or thundershowers. The opposite precipitation type is known as stratiform precipitation.

Convergence: Refers to the converging of wind vectors at a given level of the atmosphere. Low-level convergence (along with upper-level divergence), for instance, is associated with lifting of the air mass which usually leads to development of clouds and precipitation. Low-level divergence (and upper-level convergence) is associated with atmospheric subsidence, which leads to drying and warming.

Deposition: A phase change where water vapor turns directly to solid form (ice). The opposite process is called sublimation.

Dew point: The temperature at which condensation occurs (or would occur) with a given amount of moisture in the air.

Diffluent: Wind vectors spreading further apart in a two-dimensional frame of reference; opposite of confluent

Entrain: Usually used in reference to the process of a given air mass being ingested into a storm system

Evaporation: Phase change of liquid water into water vapor. Water vapor is usually invisible to the eye.

El Nino: A reference to a particular phase of oceanic and atmospheric temperature and circulation patterns in the tropical Pacific, where the prevailing easterly trade winds weaken or dissipate. Often has an effect on mid-latitude patterns as well, such as increased precipitation in southern portions of the U.S. and decreased precipitation further north. The opposite phase is called La Nina.

Front (or frontal zone): Reference to a temperature boundary with either incoming colder air (cold front) or incoming warmer air (warm front); can sometimes be a reference to a stationary temperature boundary line (stationary front) or a more complex type known as an occluded front (where the temperature change across a boundary can vary in type at different elevations).

Glaciogenic: Ice-forming (aiding the process of nucleation); usually used in reference to cloud seeding nuclei

GMT (or UTC, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Pacific Standard Time (PST) = GMT – 8 hours; Pacific Daylight Time (PDT) = GMT – 7 hours.

Graupel: A precipitation type that can be described as “soft hail”, that develops due to riming (nucleation around a central core). It is composed of opaque (white) ice, not clear hard ice such as that contained in hailstones. It usually indicated the presence of convective clouds and can be associated with electrical charge separation and occasionally lightning activity.

High Pressure (or Ridge): Region of the atmosphere usually accompanied by dry and stable weather. Corresponds to a northward bulge of the jet stream on a weather map, and to an anti-cyclonic (clockwise) circulation pattern.

Inversion: Refers to a layer of the atmosphere in which the temperature increase with elevation

Jet Stream or Upper-Level Jet (sometimes referred to more generally as the storm track): A region of maximum wind speed, usually in the upper atmosphere that usually coincides with the main storm track in the mid-latitudes. This is the area that also typically corresponds to the greatest amount of mid-latitude synoptic-scale storm development.

La Nina: The opposite phase of that known as El Nino in the tropical Pacific. During La Nina the easterly tropical trade winds strengthen and can lead in turn to a strong mid-latitude storm track, which often brings wetter weather to northern portions of the U.S.

Longwave (or longwave pattern): The longer wavelengths, typically on the order of 1,000 – 2,000+ miles of the typical ridge/trough pattern around the northern (or southern) Hemisphere, typically most pronounced in the mid-latitudes.

Low-Level Jet: A zone of maximum wind speed in the lower atmosphere. Can be caused by geographical features or various weather patterns, and can influence storm behavior and dispersion of cloud seeding materials

Low-pressure (or trough): Region of the atmosphere usually associated with stormy weather. Corresponds to a southward dip to the jet stream on a weather map as well as a cyclonic (counter-clockwise) circulation pattern in the Northern Hemisphere.

Mesoscale: Sub - synoptic scale, about 100 miles or less; this is the size scale of more localized weather features (such as thunderstorms or mountain-induced weather processes).

Microphysics: Used in reference to composition and particle types in a cloud

MSL (Mean Sea Level): Elevation height reference in comparison to sea level

Negative (ly) tilted trough: A low-pressure trough where a portion is undercut, such that a frontal zone can be in a northwest to southeast orientation.

Nucleation: The process of supercooled water droplets in a cloud turning to ice. This is the process that is aided by cloud seeding. For purposes of cloud seeding, there are three possible types of cloud

composition: Liquid (temperature above the freezing point), supercooled (below freezing but still in liquid form), and ice crystals.

Nuclei: Small particles that aid water droplet or ice particle formation in a cloud

Orographic: Terrain-induced weather processes, such as cloud or precipitation development on the upwind side of a mountain range. Orographic lift refers to the lifting of an air mass as it encounters a mountain range.

Pressure Heights:

(700 millibars, or mb): Corresponds to approximately 10,000 feet above sea level (MSL); 850 mb corresponds to about 5,000 feet MSL; and 500 mb corresponds to about 18,000 feet MSL. These are standard height levels that are occasionally referenced, with the 700-mb level most important regarding cloud-seeding potential in most of the western U.S.

Positive (ly) tilted trough: A normal U-shaped trough configuration, where an incoming cold front would generally be in a northeast– southwest orientation.

Reflectivity: The density of returned signal from a radar beam, which is typically bounced back due to interaction with precipitation particles (either frozen or liquid) in the atmosphere. The reflectivity depends on the size, number, and type of particles that the radar beam encounters

Ridge (or High Pressure System): Region of the atmosphere usually accompanied by dry and stable weather. Corresponds to a northward bulge of the jet stream on a weather map, and to an anti-cyclonic (clockwise) circulation pattern.

Ridge axis: The longitude band corresponding to the high point of a ridge

Rime (or rime ice): Ice buildup on an object (often on an existing precipitation particle) due to the freezing of supercooled water droplets.

Shortwave (or shortwave pattern): Smaller-scale wave features of the weather pattern typically seen at mid-latitudes, usually on the order of a few to several hundred miles; these often correspond to individual frontal systems

Silver iodide: A compound commonly used in cloud seeding because of the similarity of its molecular structure to that of an ice crystal. This structure helps in the process of nucleation, where supercooled cloud water changes to ice crystal form.

Storm Track (sometimes reference as the Jet Stream): A zone of maximum storm propagation and development, usually concentrated in the mid-latitudes.

Stratiform: Usually used in reference to precipitation, this implies a large area of precipitation that has a fairly uniform intensity except where influenced by terrain, etc. It is the result of larger-scale (synoptic scale) weather processes, as opposed to convective processes.

Sublimation: The phase change in which water in solid form (ice) turns directly into water vapor. The opposite process is deposition.

Subsidence: The process of a given air mass moving downward in elevation, such as often occurs on the downwind side of a mountain range

Supercooled: Liquid water (such as tiny cloud droplets) occurring at temperatures below the freezing point (32 F or 0 C).

Synoptic Scale: A scale of hundreds to perhaps 1,000+ miles, the size scale at which high and low pressure systems develop

Trough (or low pressure system): Region of the atmosphere usually associated with stormy weather. Corresponds to a southward dip to the jet stream on a weather map as well as a cyclonic (counter-clockwise) circulation pattern in the Northern Hemisphere.

Trough axis: The longitude band corresponding to the low point of a trough

Upper-Level Jet or Jet Stream (sometimes referred to more generally as the storm track): A region of maximum wind speed, usually in the upper atmosphere that usually coincides with the main storm track in the mid-latitudes. This is the area that also typically corresponds to the greatest amount of mid-latitude synoptic-scale storm development.

UTC (or GMT, or Z) time: Greenwich Mean Time, universal time zone corresponding to the time at Greenwich, England. Pacific Standard Time (PST) = GMT – 8 hours; Pacific Daylight Time (PDT) = GMT – 7 hours.

Vector: Term used to represent wind velocity (speed + direction) at a given point

Velocity: Describes speed of an object, often used in the description of wind intensities

Vertical Wind Profiler: Ground-based system that measures wind velocity at various levels above the site